POWER SYSTEM PROTECTION & CONTROL

STAGE 2A-PSP101

TEXTBOOK/WORKBOOK

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TEXTBOOK/WORKBOOK

TABLE OF CONTENTS

POWER SYSTEM PROTECTION & CONTROL

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COURSE OVERVIEW

OVERVIEW

After completion of this course, the trainee will have the necessary knowledge and skills to identify the power transformer and its accessories, instrument transformers as part of protection system, circuit breaker and their control circuits, bus bar design, and power system equipment including generator, reactive power system, grounding, insulators, and battery chargers.

OBJECTIVES

Upon completion of this course, the trainees will be able to:

- Identify the power transformer and their accessories.
- Illustrate the instrument transformers and there rule in protection system.
- Demonstrate the different types of circuit breakers and there control circuits.
- Identify the contents of power system equipment.

CONTENTS

The contents of the (2A) course material are divided into four (4) units of instructions with eighteen (18) lessons.

Text and workshop material

Unit 1	Power and Instrument Transformers
Unit 2	Circuit Breaker & Control Circuits
Unit 3	Power System Equipment

Unit 4 Fault Conditions and Calculations

DURATION

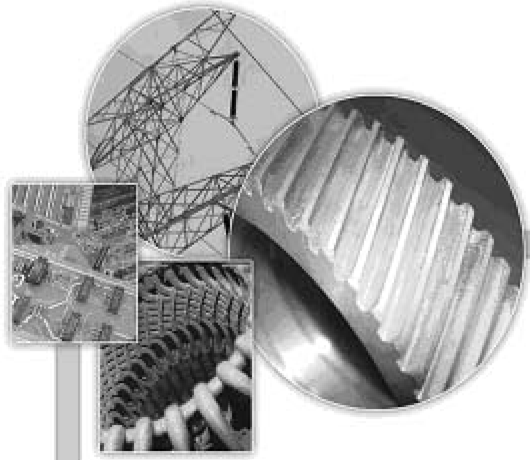
This course is for duration of nine (9) weeks to cover theoretical part, practical tasks, and field visits.

POWER SYSTEM PROTECTION & CONTROL
STAGE 2A-PSP101

PACING SCHEDULE

TEXTBOOK/WORKBOOK

Unit	Description	Duration (Hours)
1	Power and Instrument Transformers	50
2	Circuit Breaker & Control Circuits	50
3	Power System Equipment	50
4	Fault Conditions and Calculations	50
	TOTAL	**200**



UNIT 1

POWER & INSTRUMENT TRANSFORMERS

UNIT-1
POWER & INSTRUMENT TRANSFORMERS

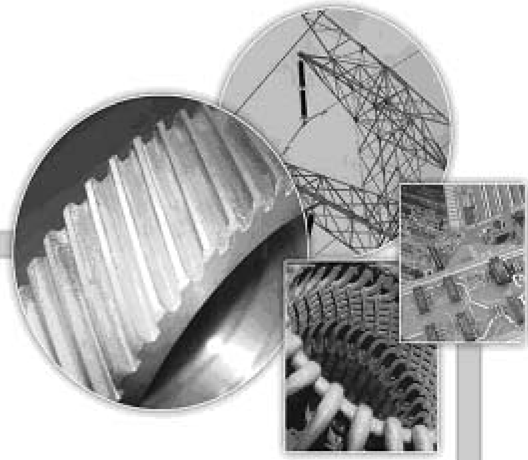
OVERVIEW

In this unit, the trainees learn the importance of power transformer with its auxiliaries such as tap changer, cooling system, metering indicators and instrument transformers. Furthermore, the unit explains the preventive maintenance (P.M) for instrument devices.

OBJECTIVES

Upon completion of this unit, the trainees will be able to:

- Identify the parts of a power transformer construction and explain its construction.
- Demonstrate the importance of tap changer.
- Illustrate the functions of instrument transformers.
- Demonstrate the primary injection through current transformers.



LESSON 1.1

POWER TRANSFORMERS

LESSON 1.1
POWER TRANSFORMER

OVERVIEW

This lesson deals with the operation of 3 phase power transformers, their construction, cooling methods, instrument devices, and Buchholz relay.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Familiarize with principles of three-phase transformers.
- Identify parts of a power transformer.
- Describe the cooling methods of power transformers.
- Familiarize with protective devices for power transformers.

<u>Task 1.1-1:</u> Inspect power transformer and its parts including Buchholz relay.

INTRODUCTION

The transformer is one of the most efficient machines ever built. Its purpose is to step up or down voltage. Briefly, it changes electric energy to magnetic energy, and then back to electric energy, by the process of mutual induction. Only 1 or 2 % of the input energy is lost in this process. There are varieties of large transformer designs, some operating at 95-98% efficiency. Although transformers differ in size and in application, they all really upon the principle of mutual inductance for their operation.

POWER TRANSFORMERS

Reliable

The efficient transmission and distribution of electricity would be impossible without power transformers. Power transformers actually used to change the voltage from one level to another and regulate the voltage level. Power transformers existing in transmission substations serve for operation at the higher voltages in the range of 69kV, 115kV, and 230kV. Fig. 1.1-1 shows an installed transformer in a substation switchyard.

Fig. 1.1-1 Substation Switchyard Includes Power Transformer

PRINCIPLES OF THREE-PHASE TRANSFORMER

The three-phase transformer is an assembly of three single-phase transformers. A certain interconnection configures the three primary windings, and another connection arranges the three secondary windings with isolation between primary and secondary. The interconnection of the transformer windings of the possible configurations are as follow:

- **Wye (Y) connection (additive or subtractive)**
- **Delta (Δ) connection (additive or subtractive)**

The (Y) connection provides a simple way to ground the winding at the star point. The (Δ) connection provides current of $\sqrt{3}$ times more of the (Y) connection and shift angle of 30^o lead or lag depending on the connection type (additive or subtractive). Figures. 1.1-2 & 3 show three-phase windings connected in a (Y) and (Δ) connection.

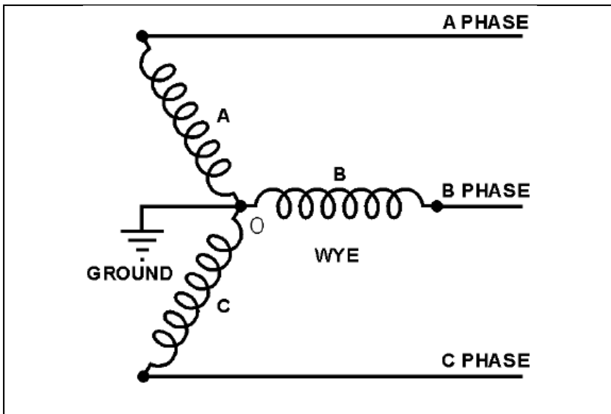


Fig. 1.1-2 Configuration of three phase Winding in a Wye (Y) Connection

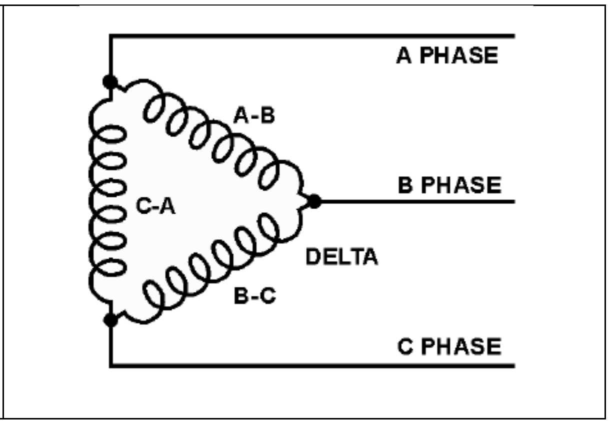


Fig. 1.1-3 Configuration of three phase Winding in a Delta (Δ) Connection

The use of each connection will be discussed in a later section. In the Wye/Wye or Delta/Delta connection, both primary and secondary have the same connection as shown in Fig. 1.1-4 & Fig. 1.1-5, respectively.

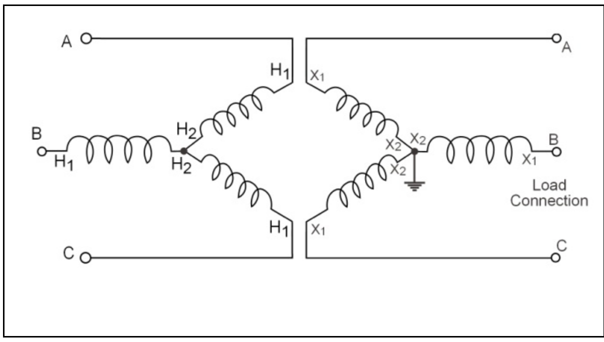


Fig. 1.1-4 Wye/Wye (Y/Y) Connection

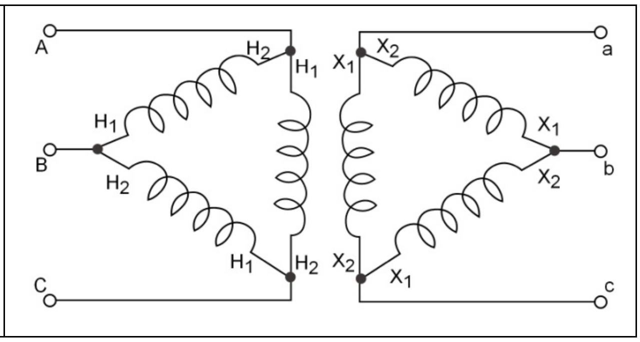


Fig. 1.1-5 Delta/Delta (Δ/Δ) Connection

In the Wye/Delta configuration, the primary is connected in Wye form while the secondary is connected in Delta form, as shown in Fig. 1.1-6. In the Delta/Wye configuration, the primary is connected in Delta form while the secondary is connected in Wye form, as shown in Fig. 1.1-7.

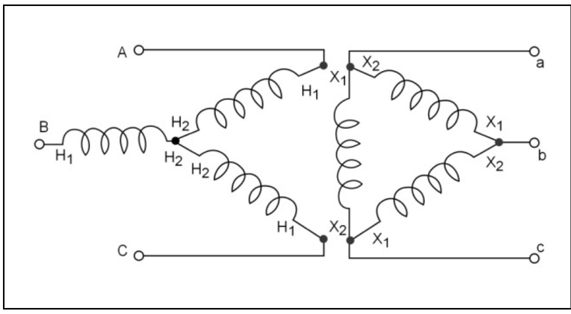


Fig. 1.1-6 Wye/Delta (Y/Δ) Connection

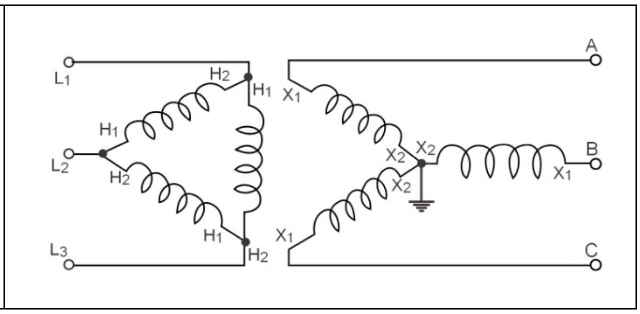


Fig. 1.1-7 Delta/Wye (Δ/Y) Connection

The need for using the connection type for each primary and secondary is determined from the configuration study of the power system, loading, fault conditions, and the need for earthing.

A power transformer in a substation is shown in Fig. 1.1-8. The power transformer is equipped with radiators for cooling by the insulating oil, oil-level gauge with alarm contacts, hot-spot-winding temperature equipment, on-load tap changer, nitrogen cylinder cabinet, sudden pressure relay, bushings, and lightning arresters.

Fig. 1.1-8 Power Transformer with associated Accessories

Fig. 1.1-9 shows the detailed parts of the power transformer.

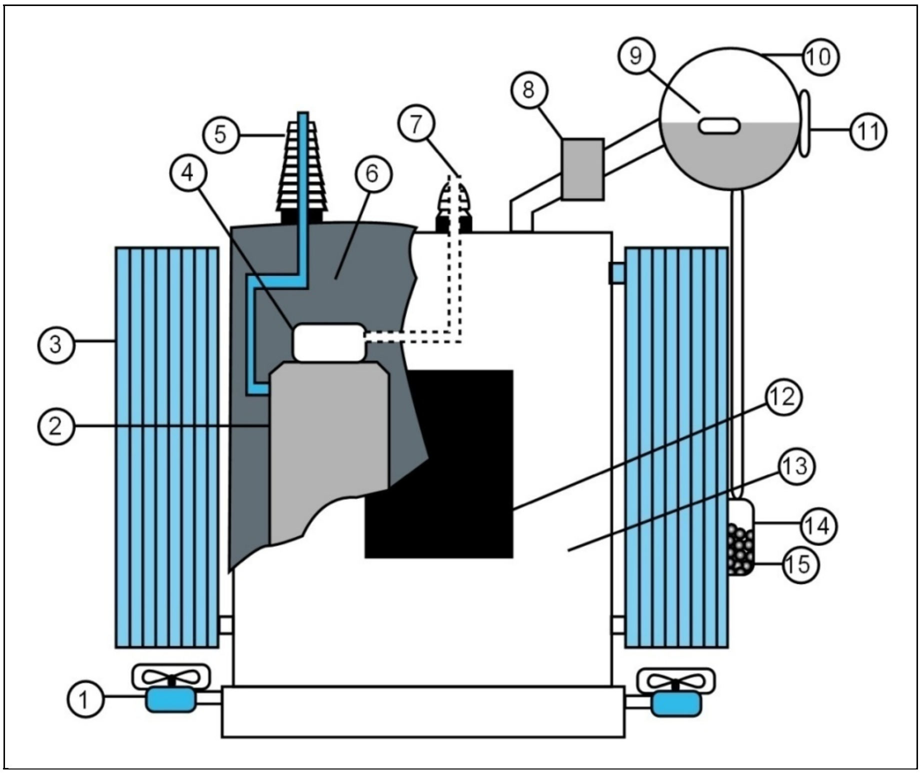


Fig. 1.1-9 Parts of Power Transformer

1- Cooling fan	2- Primary winding	3- Radiator
4- Secondary winding	5- HV Bushing	6- Transformer oil
7- LV bushing	8- Buchholz relay	9- Float
10- Conservator	11- Oil gauge	12- Control panel.
13- Oil tank	14- Dehydrating breather	15- Silica gel

TRANSFORMER COOLING METHODS

Because of loading of the power transformer, a power is dissipated producing amount of heat. The heat must be eliminated from the transformer by cooling methods. Natural cooling is used with the small transformers, oil, radiators, and air fans are used with the large power transformers.

The following table shows various methods of cooling according to British standards **(BESA),** American standards **(ANSI)** and Canadian Standards **(CSA)**.

COOLING METHOD	CSA DESIGNATION	ANS1 DESIGNATION	BESA DESIGNATION
Oil-Immersed, Natural-Circulation Self-Cooled	ONAN	OA	ON
Oil-Immersed, Natural-Circulation, water-Cooled	ONWN	OW	OW
Oil-Immersed, Natural-Circulation, Forced air-Cooled	ONAF	FA	OB
Oil-Immersed, Forced-Oil, Water-Cooled	OFWN	FOW	OFW
Oil-Immersed, Forced-Oil, Forced-Air Cooled	OFAF	FOA	OFB
Oil-Immersed, Natural-Circulation, Forced-Air-Cooled (Second stage of Forced-Air)	ONAF/ONAF	FA/FA	

Table 1.1-1 Transformer Cooling Methods

TRANSFORMER CORE AND WINDING

CORE TYPE

There are two main shapes of cores used in laminated-steel-core transformers. One is the **CORE TYPE**, so named because the core is shaped with a hollow square through the center. Fig. 1.1-10 illustrates this shape of core.

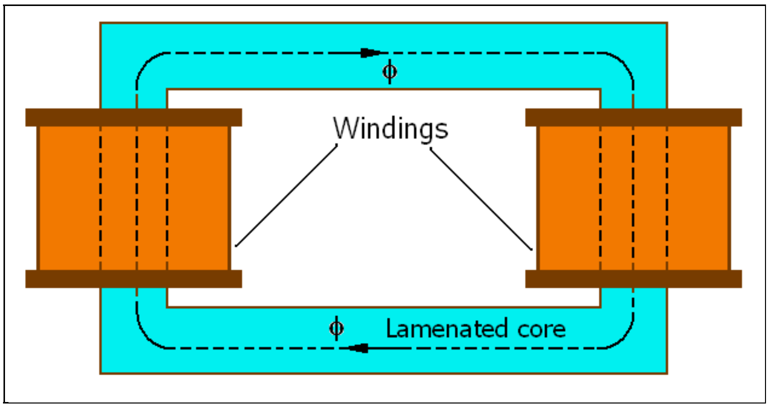


Fig. 1.1-10 Core Type

SHELL TYPE CORE

It is the most popular and efficient transformer core is the **SHELL CORE**, as illustrated in Fig. 1.1-11. Each layer of the core consists of E- and I-shaped sections of metal. These sections are butted together to form the laminations.

Fig. 1.1-11 Shell Type

The core of three-phase power transformer has three legs and made from high permeability grade laminated silicon steel sheets to minimize iron losses and eddy currents. The windings are wound on the legs, as shown in Fig. 1.1-12. In a core-form transformer, the standard coil is a concentric arrangement with higher voltage outer winding and a low voltage inner winding with taps from outer windings.

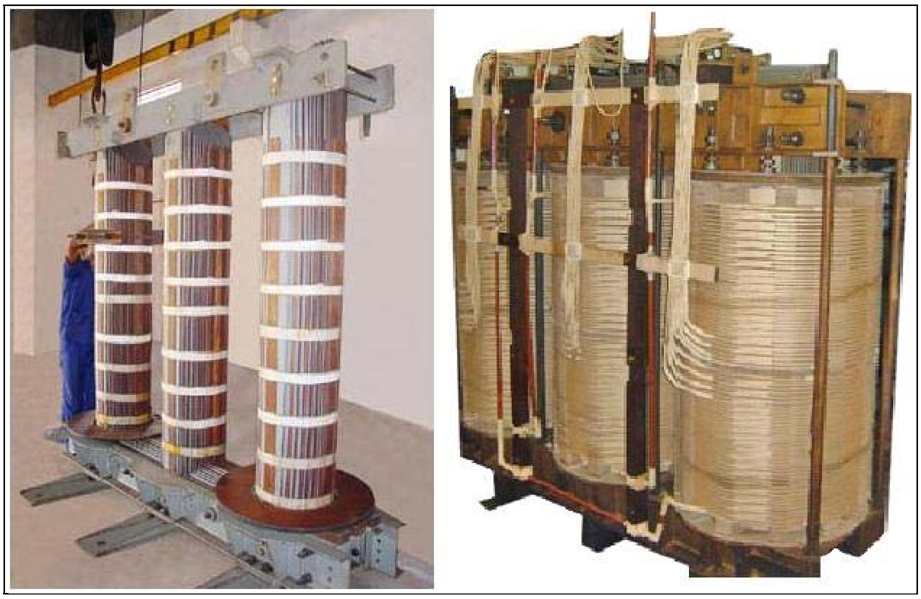


Fig. 1.1-12 Transformer core and Windings

TRANSFORMER TANK

Core and windings of the transformer are immersed in oil in the transformer tank. The tank is filled with oil to cool the windings as well as providing insulation; the insulating oil increases the insulation of the windings.

TRANSFORMER RADIATOR & COOLING FANS

Radiators are mounted in power transformer to provide cooling of the oil. The heat is carried out by convection. The core gives up its heat to the oil and the oil in turn gives up the heat to the metal of the radiators by conduction. Heat transfers from radiator to the surrounding air. Fans are mounted on the transformer radiators to provide forced air that will increase cooling of the oil (see Fig. 1.1-13). These fans cause a faster heat

exchange and so, will improve the capability of the transformer and in this case, the transformer can be loaded 20-30% over its power without operating cooling fans. The fans operate automatically when the temperature of the oil exceeds definite value.

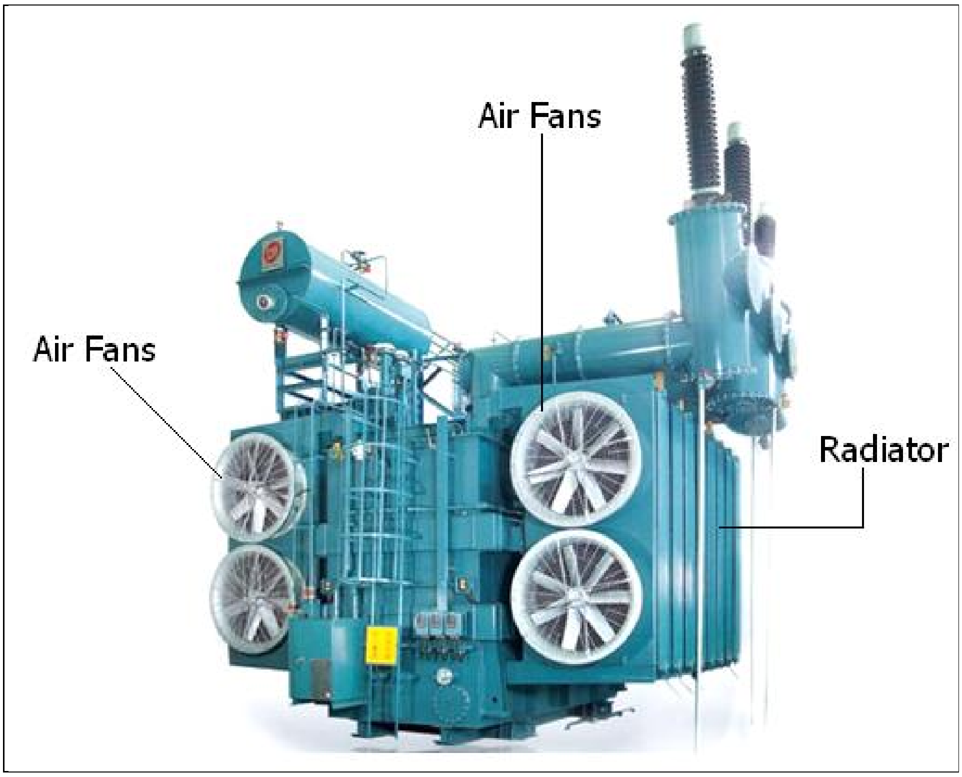


Fig. 1.1-13 Transformer Cooling

TRANSFORMER INDICATING INSTRUMENTS

There are some indicating instruments for transformer, which provide visual indication of both normal and abnormal conditions within the transformer.

OIL LEVEL GAUGE

All power transformers are equipped with an oil level gauge. Normally it is mounted on the conservator, as shown in Fig. 1.1-14. There are many types of level gauges. One of them is the magnetic oil level gauge, as shown in Fig. 1.1-15. Most separate oil-filled compartments, such as those associated with load tap changer equipment; also may have their own level gauge. These operate on a simple float principle and

may provide visual indication only, or may be equipped with alarm contacts to indicate high or low-level conditions. At ambient temperature of 25°C with no load, the gauge should read, approximately, mid-range.

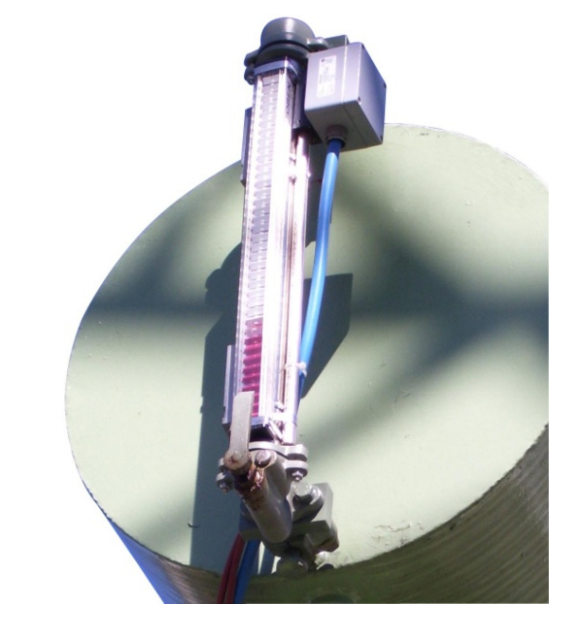


Fig. 1.1-14 Supported Oil Level Gauge on the Conservator

Fig. 1.1-15 Magnetic Oil Level Gauge

PRESSURE GAUGE

This gauge is available for use on all sealed type power transformers. Several types are available but all are direct reading and indicate the pressure or vacuum on the tank (see Fig. 1.1-16). Under normal operating conditions, the gauge should read a positive or negative pressure. Should the gauge read zero consistently, there is a possibility of an air leak into the transformer. In any suspected cases, the leaks should be inspected and corrected immediately.

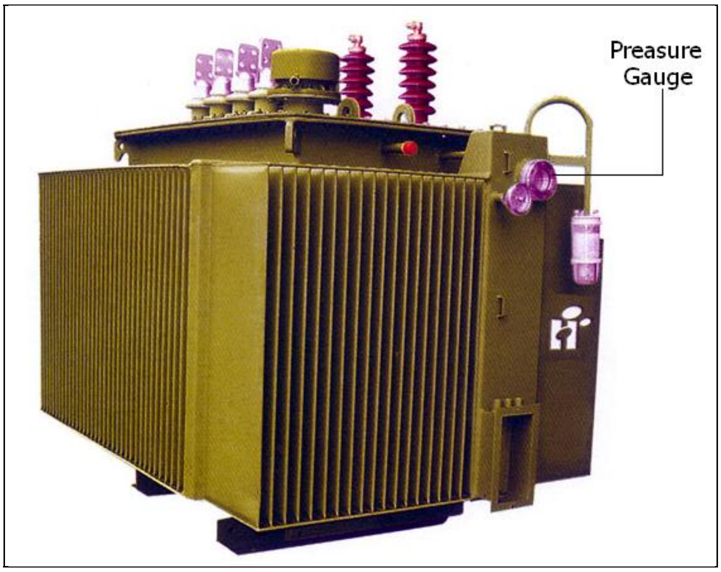


Fig. 1.1-16 Oil Pressure Gauge

Fig. 1.1-17 Pressure Gauge

OIL TEMPERATURE GAUGE

Oil Temperature gauge senses and indicates the top oil temperature in the transformer tank. It may be a normal bimetal type or digital type. The oil gauge is located in a well inside the tank filled with little quantity of oil separate from the tank oil, as shown in Fig. 1.1-18. It can be disassembled for inspection, repair, or replacement without lowering the oil level.

Fig. 1.1-18 Oil Temperature Gauge and its Well Accessories

The temperature gauge is usually equipped with alarm contacts to indicate abnormally high temperatures, as shown in Fig. 1.1-19. This accessory gives a measure of protection against high thermal conditions caused by overloads but, due to the oil characteristics, it may respond too slowly under abnormal loading conditions to provide adequate protection in all cases. Top oil thermometers are provided on all power transformers. Capillary tubing for remote or ground level indication is available.

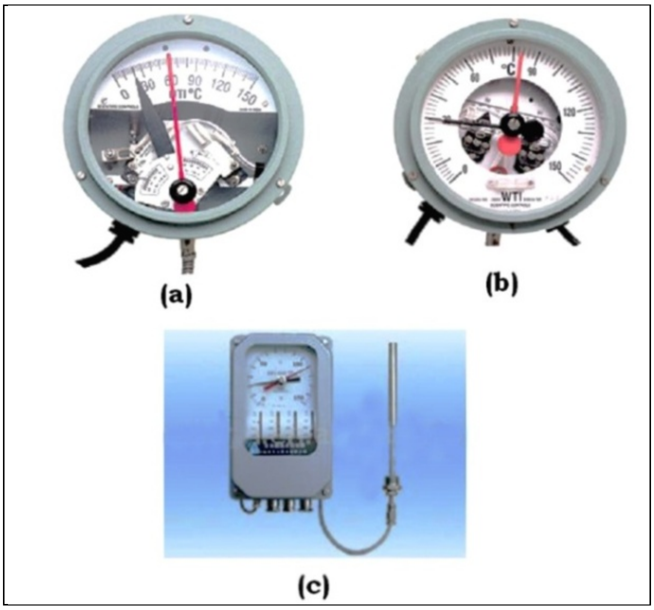


Fig. 1.1-19 Oil Temperature Indicators

WINDING TEMPERATURE INDICATOR

This instrument provides a high degree of loading control and protection by sensing the hot-spot winding temperature and rapidly following all conditions of load changes. It indicates the combined temperature of the top oil and the heating effect within the winding due to load current. It may be a normal bimetal type or digital type. That gauge is inserted in a well on the tank top and can be removed without lowering the oil (see Fig. 1.1-20).

Fig. 1.1-20 Winding Temperature Indicator & Switch

CONSERVATOR

As shown in Fig. 1.1-21 & Fig. 1.1-22, the conservator is an expansion tank system to balance the oil pressure of the main tank. During transformer loading, the excessive heat results in transferring/breathing out some oil to the conservator from the main tank. Drop of the load results in decreasing heat and the main tank breathes in again and receives oil from the conservator.

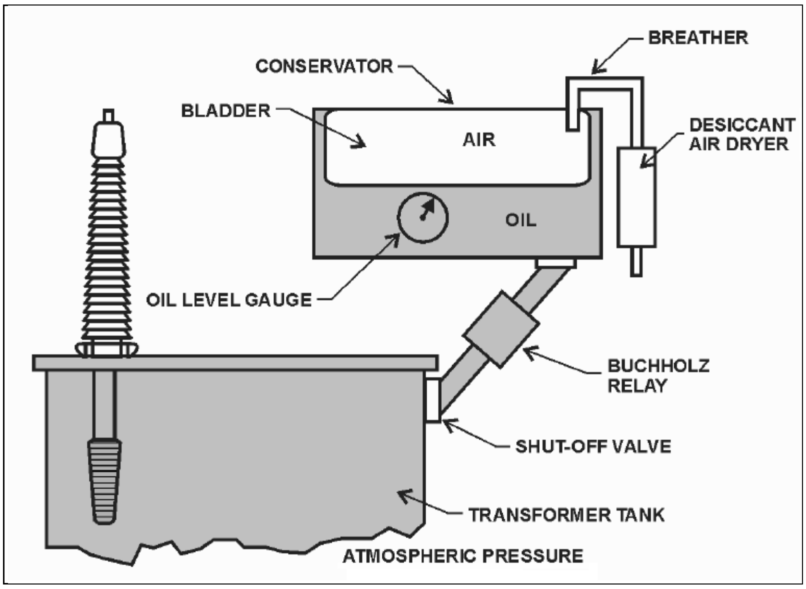


Fig. 1.1-21 Conservator with Bladder

Fig. 1.1-22 Transformer Tank with Conservator and Relief Vent

PRESSURE RELIEF VENTS

As shown in Fig. 1.1-22, oil filled power transformers are equipped with some type of pressure relief device. They are designed to relieve high pressures and in doing so, limit the possibility of tank rupture. The simplest form of pressure relief vent is the

rupturing diaphragm type. The diaphragm material ruptures at a pre-determined pressure.

MOTOR FAN CONTROLLER

The motor fans' controller monitors the oil temperature and controls the cooling motor fans, as shown in Fig. 1.1-23. Table 1.1-2 provides the recommended settings for temperature devices for oil-immersed power transformers that set for Ghaslan power plant transformers according to SEC Standard.

Top Oil Temperature	**Winding Temperature**	**Action**
60 °C	80 °C	Start air fans, stage 1
70 °C	85 °C	Start air fans, stage 2
80 °C	90 °C	Start oil pumps
85 °C	95 °C	Alarm, non urgant
95 °C	105 °C	Alarm, urgant/ trip

Table 1.1-2 Sequence of Temperature rise and Control Response

Fig. 1.1-23 Transformer Cooling Fans

If SCADA is not available, the transformer shall be off-load if the top oil temperature or winding temperature reaches 95°C or 105°C, respectively.

BUCHHOLZ RELAY

Buchholz relay is located between conservator and the main tank, as shown in Fig. 1.1-24 and 25. Buchholz relay generates trip and/or alarm signal when the transformer develops an internal fault or trouble. All faults in the transformer result in the localized heating and breakdown of the oil due to winding faults, thus causing oil decomposition and releasing gases. Buchholz relay starts operation by the buoyancy of the gas produced in the transformer overheating or the rushing current of the oil. It is possible to determine the cause of trouble by checking the quality and color of the gas and quantity.

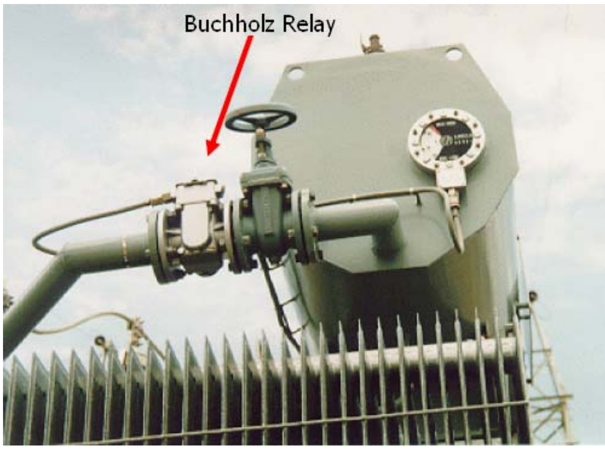


Fig. 1.1-24 Buchholz Relay

Fig. 1.1-25 Installing of Buchholz Relay with the Conservator

DEHYDRATING BREATHER

All power transformers other than totally sealed types have some sort of breather. As the oil expands and contracts due to temperature cycling, air enters or leaves the conservator tank or compartment such as that associated with an on-load tap changer.

The simplest breather contains an oil filter to prevent bugs and foreign matter from entering and is so designed that rain, dust, etc., cannot enter the transformer. The breather permits ambient air outside without its associated moisture content to come on the surface of the oil.

Dehydrating breathers, as shown in Fig. 1.1-26, absorb moisture from the air entering the transformer. Silica-gel crystals are used as the drying chemical material in dehydrating breathers. Some type of crystals are blue in color when dry and turn pale pink as they become moist, at which time they should changed.

Some amount of oil is supplemented to the breather to capture the foreign objects in the air before passing through the Silica gel.

Fig. 1.1-26 Different types of Silica gel & dehydrating breather

TERTIARY WINDING

Tertiary windings generally serve one of two purposes. One purpose is to provide an additional secondary different voltage for the auxiliary equipment of the station such as lighting, alarms, battery chargers, fire fighting, communication, and anunciators.

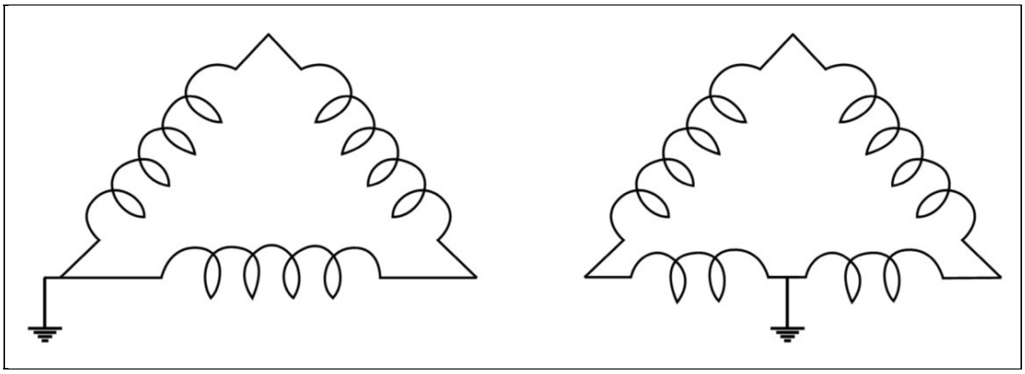


Fig. 1.1-27 Tertiary Winding Connection and Grounding Methods

The other purpose for a tertiary winding is to provide a closed-circuit path for zero-sequence currents/fluxes. That is most typically the case with transformer application where system must be connected in Wye-Wye (star-star) configuration. With a Wye-Wye transformer, the only path for zero-sequence flux is the tank of a transformer (in case of three separate phases transformer bank, even that do not exist). The tank is a high-impedance path so that the resulting zero sequence impedance looking into the transformer is very high. In addition, the circulation of zero sequence current through the tank will cause the tank to heat and lead to paint failure. A tertiary winding presents a low impedance path to zero sequence currents, thereby reducing the zero sequence impedance presented to the outside world, while avoiding the problem of tank heating.

Grounding one corner terminal of the delta tertiary winding Fig. 1.1-27 has several advantages and disadvantages, as listed below.

Advantages:

- Stabilize voltages of the ungrounded phases.
- Reduce the generation of transient over voltages.
- Provide a method for protecting electrical distribution systems when used in combination with equipment grounding.

Disadvantages:

- The system is unable to supply dual-voltage service for lighting and power loads.

- It requires a positive identification of the grounded phase throughout the system.
- A higher line-to-ground voltage exists on two phases than in a neutral grounded system.
- Most electrical distribution equipment is not rated for use on this system.
- Fault switching (opening) is much more severe for the clearing device, and ratings may be greatly reduced.

Due to its disadvantages, the corner-grounded delta system has little reason for modern day use:

The corner grounding may provide a path for flow of the Zero-Sequence current through the HV neutral, which can be sensed by providing a protection circuit.

For 3-phase core type power transformer, when a corner of tertiary is grounded, the other 2 phases experience a situation like Neutral shifting occurs. This will give rise to an unbalanced voltage to the other 2 phases to some extent.

It is preferred to leave the tertiary Delta winding floating in isolation so that zero sequence current flows in the loop of the delta tertiary winding.

For the same reason, the inrush current may be reduced in Isolated Tertiary condition rather than a grounded Tertiary condition.

SUMMARY

- 3-phase Power transformer may be an assembly of three single-phase transformers.
- Transformer winding has two types of connections star or delta.
- Power Transformer is cooled naturally, by oil, radiator or forced by air fans and oil pumps
- Breather protects the transformer oil from impurities and absorbs moisture.
- Conservator compensates for expansion and contraction of oil in the oil tank during breathing.
- Buchholz relay produces alarm and trip signals at the tank fault condition.

- Tertiary winding provides supply voltage for substation auxiliaries.
- Tertiary winding also provides closed path for zero sequence current.

GLOSSARY

Permeability:	The ability for the magnetic field to pass through the objects
Capillary:	Narrow tube
Buoyancy:	The ability to float due to low density
Heat exchange:	Method facilitating to get rid of heat
Gauge:	Measuring instrument
Immersed:	Covered with liquid all round
Silica gel:	Chemical material used to absorb moisture
Conservator:	Small oil tank above the transformer main tank
Radiator:	Group of closed loop tubes to circulate the oil for cooling
Buchholz relay:	Type of mechanical protective relay used to protect against oil gassing
Tertiary winding:	Extra third secondary winding

REVIEW EXERCISE

Select the suitable answer for each of the following:

1- The delta connection winding provides:

a) Phase shift of 180^o.

b) Good ground connection.

c) Current $\sqrt{3}$ times more than current of (Y) connection

d) The same facilitating (Y) connection

2- Conservator is used to:

a) Take oil sample for analysis.

b) Cool the tank oil.

c) Balance pressure of the tank.

d) Treat oil from dust.

3- Relief vent is used to:

a) Transfer some oil out to equalize pressure.

b) Treat oil from dust.

c) Take oil sample for analysis.

d) Cool the tank oil.

4- Buchholz relay is used to:

a) Monitor the oil level.

b) Measure the oil pressure.

c) Measure the oil temperature.

d) Provide alarm & trip signals.

5- Silica-gel is used to:

a) Absorb moister from air entering to conservator.

b) Cool the tank oil.

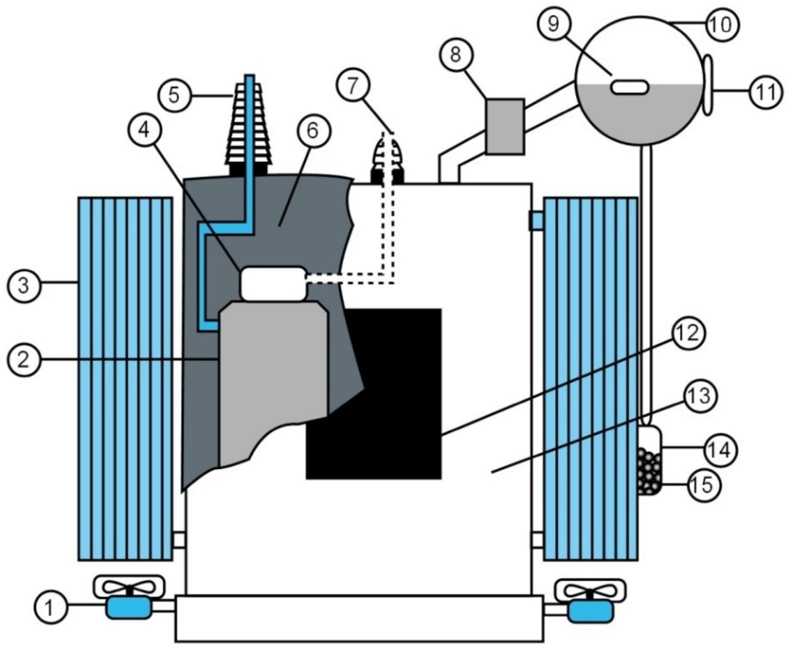
c) Compensate pressure of the tank.

d) Transfer some oil to equalize pressure.

6- Tertiary delta winding is grounded to:

a) Operate the auxiliary equipment.	b) Reduce the transient over voltages.
c) Provide Phase shift of 180^o.	d) Increase load current by $\sqrt{3}$ times more.

7- Look at the following power transformer figure and identify the number of each part.



( ) Buchholz relay	( ) Radiator	( ) Secondary winding
( ) Oil gauge	( ) Dehydrating breather	( ) Conservator
( ) Cooling fans	( ) Oil tank	( ) Silica gel
( ) Primary winding	( ) Low voltage Bushing	( ) Transformer oil
( ) Float	( ) Control Panel	( ) High voltage bushing

TASK 1.1-1
INSPECTION FOR POWER TRANSFORMERS & IDENTIFYING ITS PARTS

OBJECTIVES

Upon completion of this task, the participant will be able to:

- Inspect power transformer & identify parts.
- Demonstrate Buchholz relay alarm and trip signals.

TOOLS, EQUIPMENT & MATERIALS

Three-phase Power transformer at Transmission Stations.

SAFETY PRECAUTIONS

The participants must wear safety shoes and helmets.

PROCEDURE

1. Given the power transformer, inspect its main parts.
2. Read and record the transformer nameplate information.
3. Identify the cooling method of the transformer.
4. Identify oil level gauge of the transformer and state the function.
5. Identify oil temperature indicator and state the function.
6. Identify the transformer conservator and state the function.
7. Identify winding temperature indicator and state the function.
8. Identify silica-gel breather and state the function.
9. Identify pressure relief vent and state the function.
10. Identify Buchholz relay and state the function.

11. Identify transformer control panel and state the function.
12. Identify transformer HV bushings and state the function.
13. Identify transformer LV bushings and state the function.
14. Identify cooling fans and state the function.

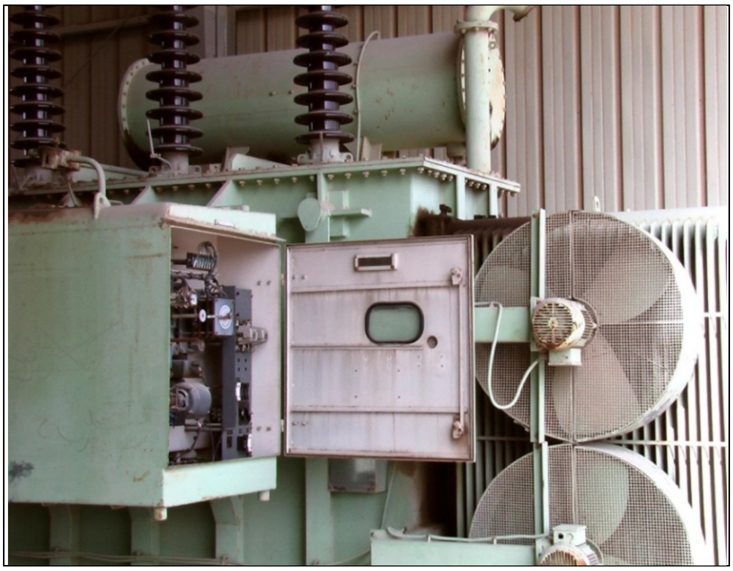


Fig. 1-1 Power Transformer for the Performance Task

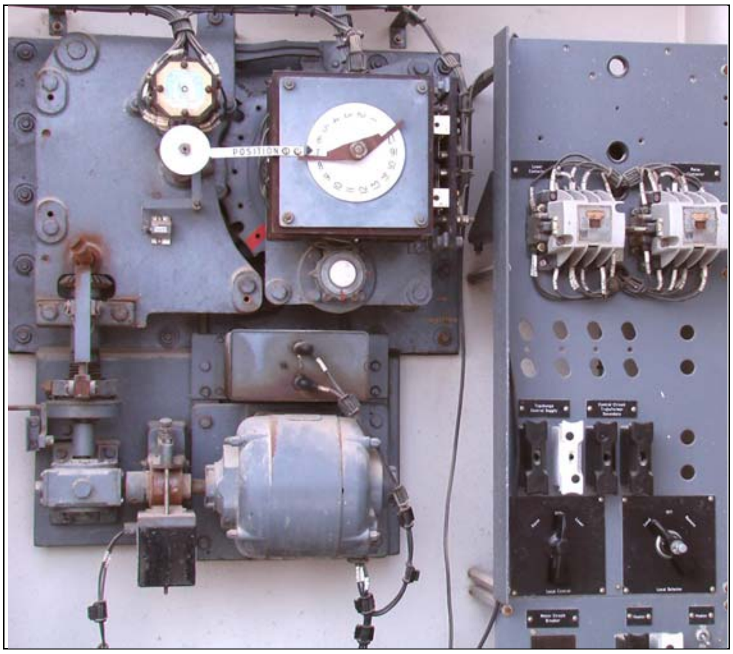
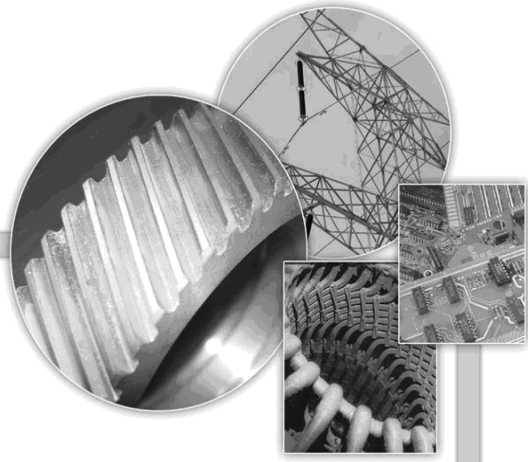


Fig. 1-2 Motor Fan Controller



LESSON 1.2

TRANSFORMER TAP CHANGERS

LESSON 1.2
TRANSFORMER TAP CHANGERS

OVERVIEW

This lesson identifies the parts of tap changers for power transformers describing its motorized and manual operation in transmission and distribution substations.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Familiarize with no-load tap changers.
- Familiarize with on-load tap changers.
- Identify parts of on-load tap changer.
- Describe sequence of operation of the tap transition.

INTRODUCTION

During the operation of the electrical network, the actual value for the system voltage fluctuates up and down from the nominal voltage, due to a large variation in the load. Transformer tap changer is a way to regulate and stabilize the system voltage. The idea is to change the turns-ratio by adding or removing some turns from the high-tension side of the transformer winding. Several ways are used to obtain the desired results.

There are two methods of tap changing:

- Manual (NO-Load) tap changer (NLTC)
- Automatic/ Manual (ON-Load) tap changer (OLTC)

The range of tap changing to raise or lower the secondary voltage is ± (5- 10) % of the rated voltage. A tap changer may be on the primary and secondary winding of some power transformers.

NO-LOAD TAP-CHANGER (NLTC)

Manual (No Load) Tap Changer is used in distribution transformers where the tap has to be changed by hand using a selector located on the outside of the tank. To change the tap, simply turn the selector handle to the desired tap position, as shown in Fig. 1.2-1. Before changing the tap manually, the transformer shall be de-energized.

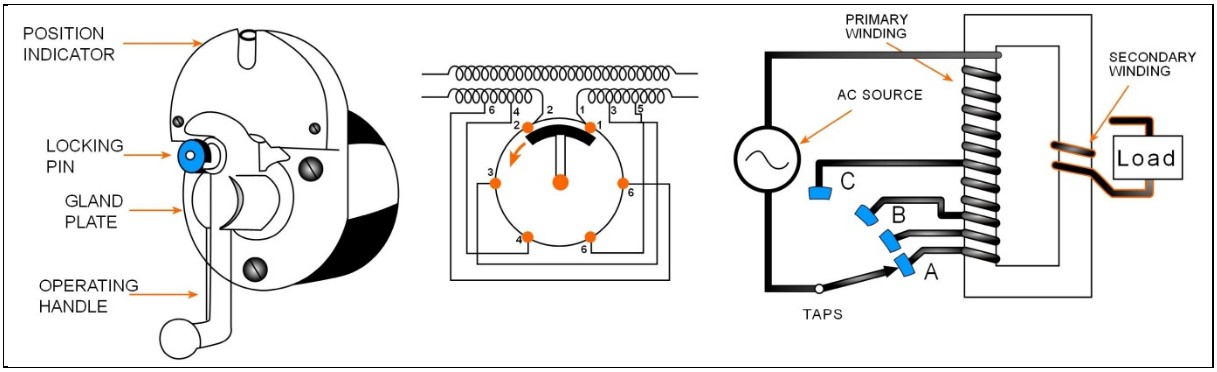


Fig. 1.2-1 No-Load Tap Changer

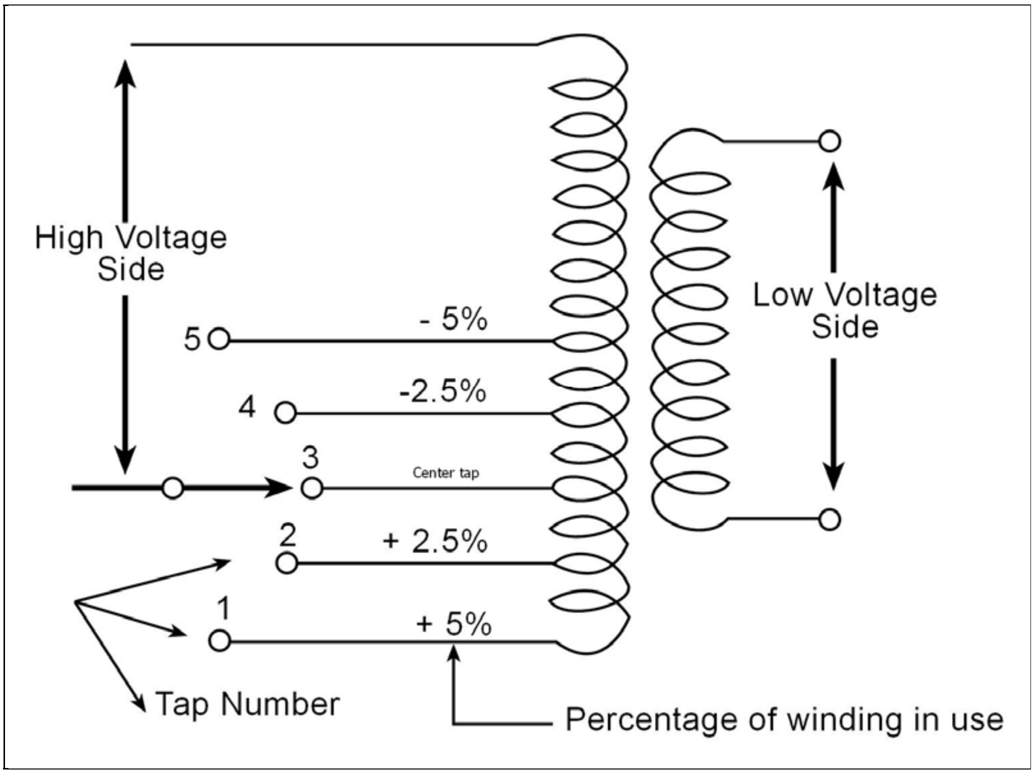


Fig. 1.2-2 OFF-Load Tap Changer

The transformer high voltage winding is "tapped" with leads connected to respective terminals to vary the number of turns. For the larger type of no-load tap changer, a crank handle is connected through the cover or the tap may be changed with a wheel.

ON-LOAD TAP-CHANGER (OLTC)

This type of tap changer is used when the need to regulate the system voltage without disconnecting the transformer from the network. On-load tap-changer simulates the use of an autotransformer with complicated switching for the high voltage circuit arrangement. The information regarding the switching sequence must be available and ready for each transformer. A tap changer can function automatically if designed with additional control circuits. It receives a voltage sample and determines, which step number of the tap changer winding must be operated and use this value to manipulate the motor position to achieve the desired function.

Automatic tap changers are used for large power transformers and for voltage regulators. The typical simplified diagram in Fig. 1.2-3 illustrates the required tools to

transfer the tap from one position to another. These tools are selector switch, vacuum switch, and bypass switch.

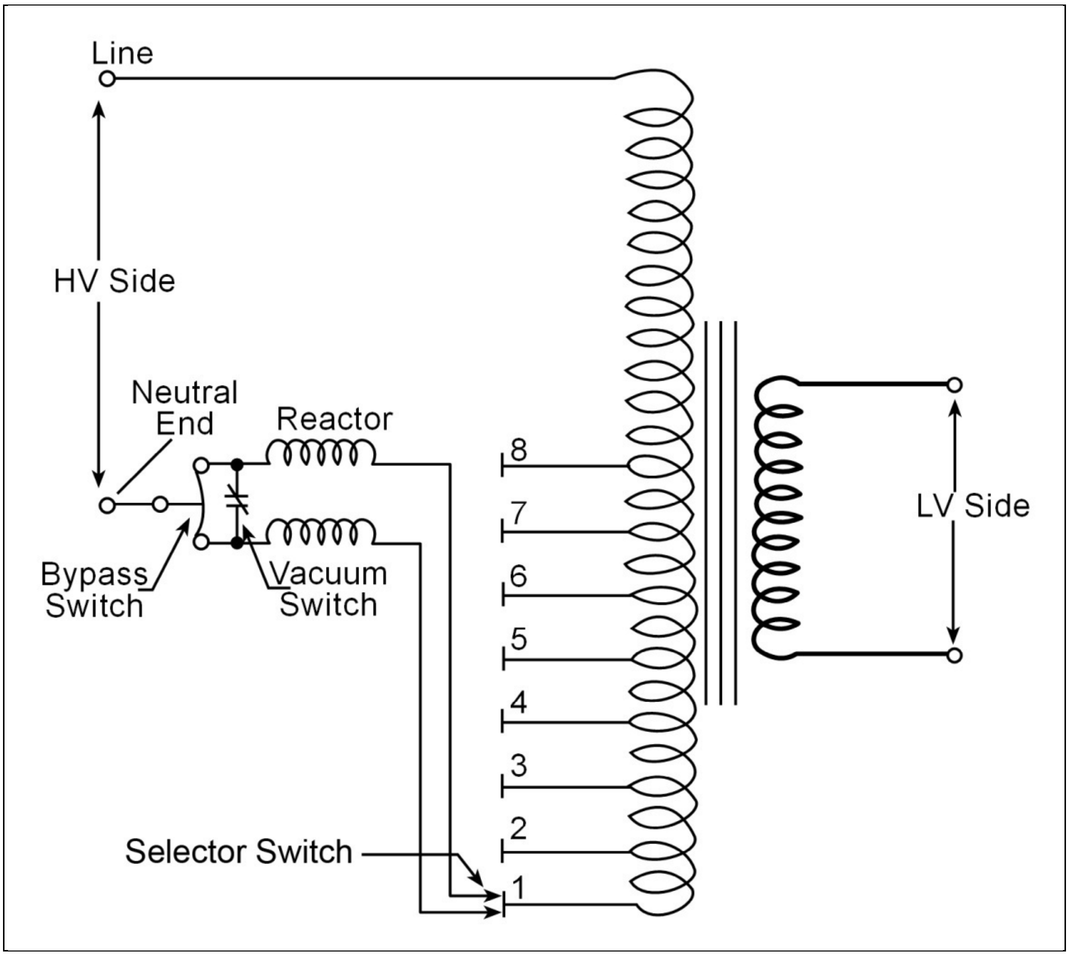
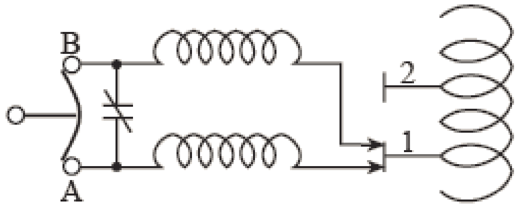


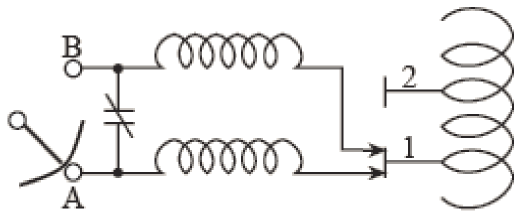
Fig. 1.2-3 ON-Load Tap-Changer

The sequence of tap changing requires ten steps in the example shown in Fig. 1.2-4. Note that the sequence of operation of the selector switch, the vacuum switch, and the bypass switch takes place, automatically, through the driving motor with an operating mechanism to operate the system sequence.

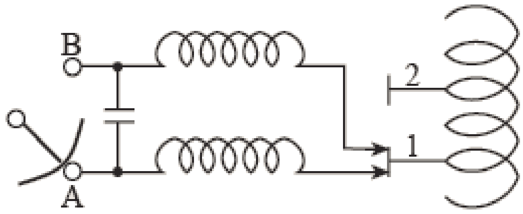
Fig. 1.2-5 shows an example for tap changer (MR type).



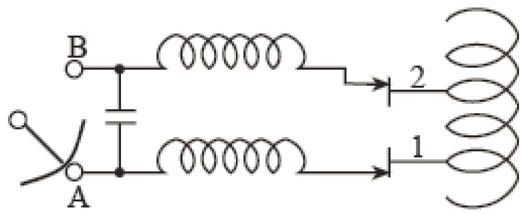
(1) Position before transition.



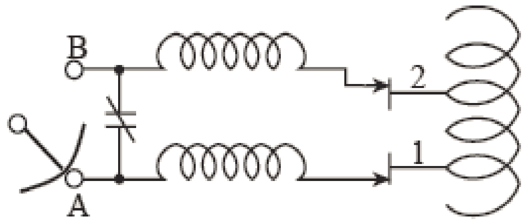
(2) Move bypass switch to point A.



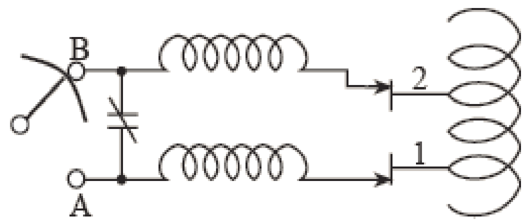
(3) Open vacuum switch.



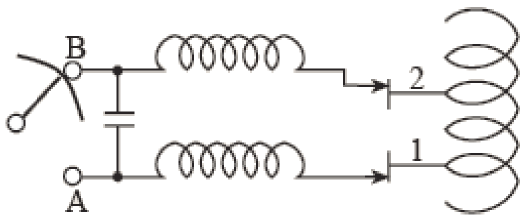
(4) Move selector switch to point 2.



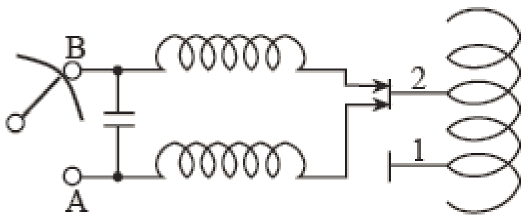
(5) Close vacuum switch.



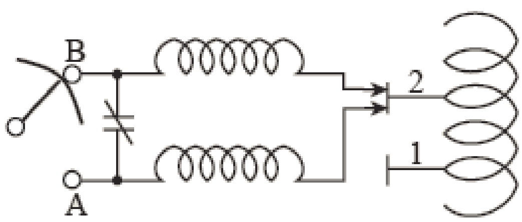
(6) Move Bypass switch to point B.



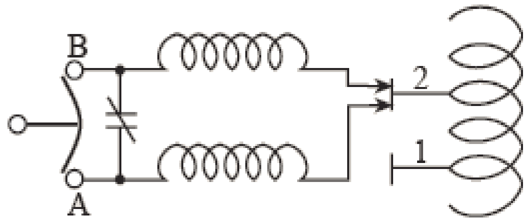
(7) Open vacuum switch.



(8) Move selector switch to point 2.



(9) Close vacuum switch.



10) Move Bypass switch between A & B.

Fig. 1.2-4 Sequence of Automatic Tap Changing

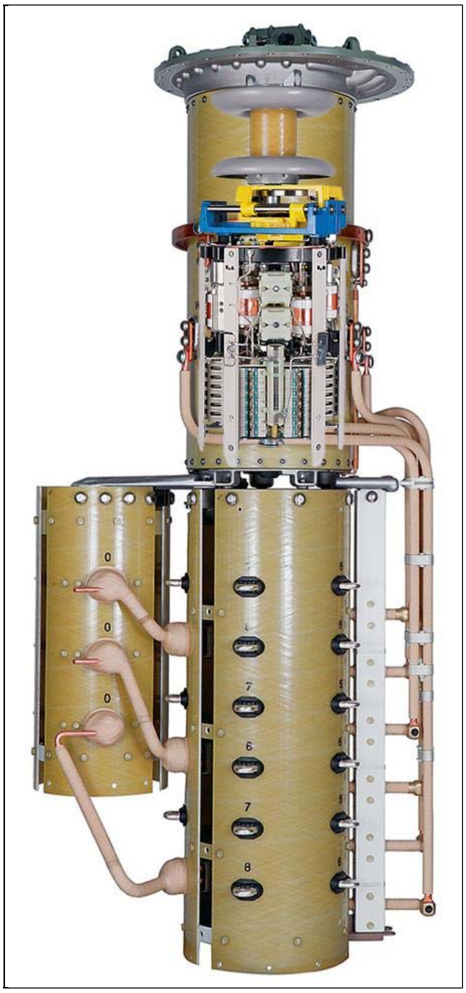


Fig. 1.2-5 ON-Load Tap Changer Type MR

The main elements of the ON-Load tap changer are driving motor, transfer switches, transition reactors, tap selector switch, and bypass switch.

A. DRIVE SYSTEM

A driving motor provides power for the drive operation.

B. TAP SELECTOR SWITCH

The tap selector switch is used to engage the tap connections on the tapped winding.

C. LOAD TRANSFER (DIVERTER) SWITCH

The load transfer switch is a device by which the load current is transferred from one tap to the next after a tap change has been initiated. It switches the circuit on and off.

D. USING RESISTORS OR REACTORS

With OLTC transformer, this is achieved mainly by two methods:

- By using combined load diverter resistances and tap selector switches.
- By using combined diverter reactors and tap selector switches.

The resistors or reactors are employed as impedance to limit the circulating current developed when bridging the taps.

TAP CHANGING OPERATION

The motor drive unit is initiated by a push button or voltage control relay and the tap selector coupled to the drive changes the tap. The diverter switch diverts the current and the transition resistors or reactors prevent the current breaking.

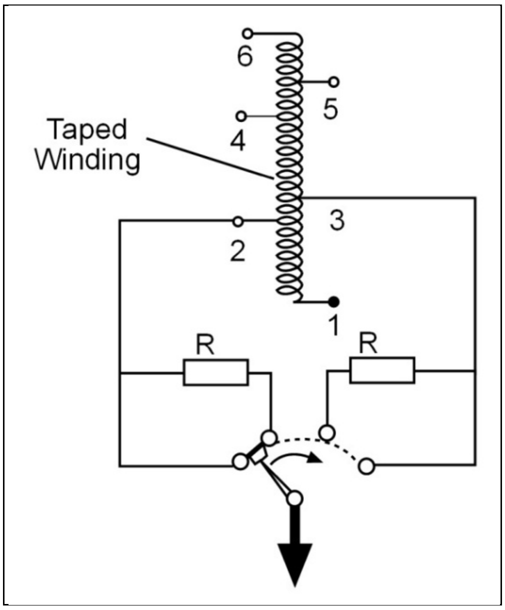


Fig. 1.2-6 On-Load Tap Changing (OLTC) Operation

The sequence of operation of tap selector and diverter switch is such that the tap is changed without interruption in the current in the main transformer winding, as shown in Fig. 1.2-6. Hence, the tap can be changed without sparks or interruption in load current.

TAP CHANGER MOTOR CONTROLLER

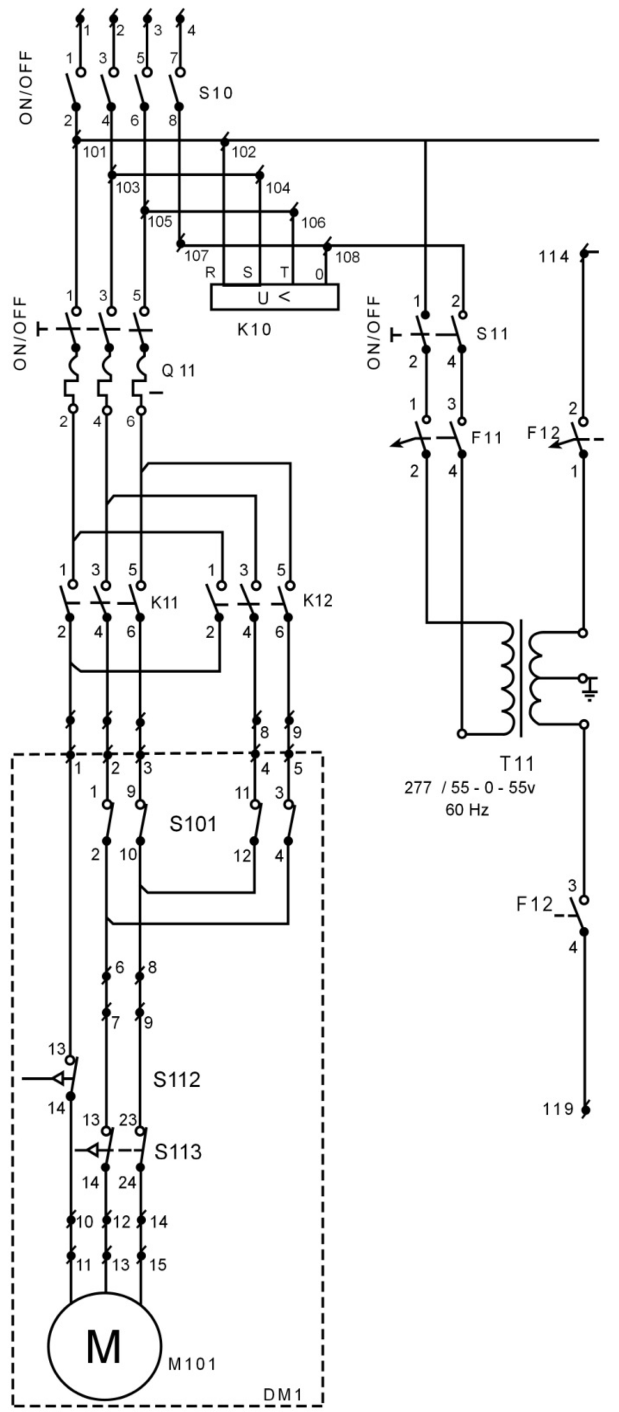
Tap changer motor controller moves the tap position up or down, according to the need to regulate the phase voltage, automatically. It consists of voltage sensor, which receives voltage signal from voltage transformer and compares it with the preset nominal voltage When a drop in the phase voltage occurs, the controller operates the motor to change the tap position by one step up and the opposite is done when the phase voltage increases and the controller operates the motor to change the tap position by one step down

Tap changer can be operated manually, according to selector switch shown in the schematic diagram (Fig. 1.2-7) for the motor control circuit in the–following tap changer example.

EXAMPLE FOR TAP CHANGER CONTROLLER

1. Construct the motor drive power circuit of Fig. 1.2-7, using high light marker to follow the driving current from the three-phase supply to the motor.
2. The tap changer controller consists of two circuits, motor drive power circuit, shown in Fig. 1.2-7, and control circuit, shown in Fig. 1.2-8.
3. Transformer T_{11} on the motor drive circuit is feeding the control circuit through terminals 114 & 119.
4. Follow and inspect the motor forward and reverse operation through contacts (K_{11}) & (K_{12}), respectively.
5. To operate the motor forward, contacts (K_{11}) close (Fig. 1.2-7) through energized contactor (K_{11}) shown in-Fig. 1.2-8.

6. Both the ON/OFF switches, the main supply switch (S_{10}) & thermal overload switch (Q_{11}), are closed during tap changing operation.
7. Identify the control transformer (T_{11}) input voltage when output is 277 / 55-0-55V.
8. The controller has two modes of operation (Manual & Automatic) through the selector switch (S_{12}).
9. In case of Manual-Raise operation, (DPDT-S_{12}) and (4P3T-S_{13}) are set at position (1, 5) and (1, 9), respectively, energizing only 1-1 circuit.
10. In case of Manual-Lower operation, (DPDT-S_{12}) and (4P3T-S_{13}) are still set at position (1, 5) and (1, 9), respectively, energizing only 5-9 circuit.
11. In case of automatic rise or lower operation, (S_{12}) and (S_{13}) are set at position (3, 7) and (3, 11), energizing only 3-3 or 7-11 circuit, respectively.
12. Automatic position is working when voltage relay unit senses the voltage level as compared to the set point and makes decision to increase (raise) or decrease (lower) the voltage.
13. The output of voltage relay operates the driver mechanism (DMI) to close (S_{105}) for raising the voltage or (S_{106}) for lowering the voltage.



S_{10}: Switch main supply

Q_{11} Motor operation with (thermal, magnetic overload.)

$K_{11,\ 12}$: Motor Contactors

S_{112}: S_{113} : Aux. Switch (open, its contacts when the tap changer operated by hand to disconnect the motor circuit)

T_{11}: Control Transformer

S_{11}: Switch of control supply

F_{11}: Protection Switch for the control transformer

Fig. 1.2-7 Motor Drive Power Circuit for Tap-Changer Controller

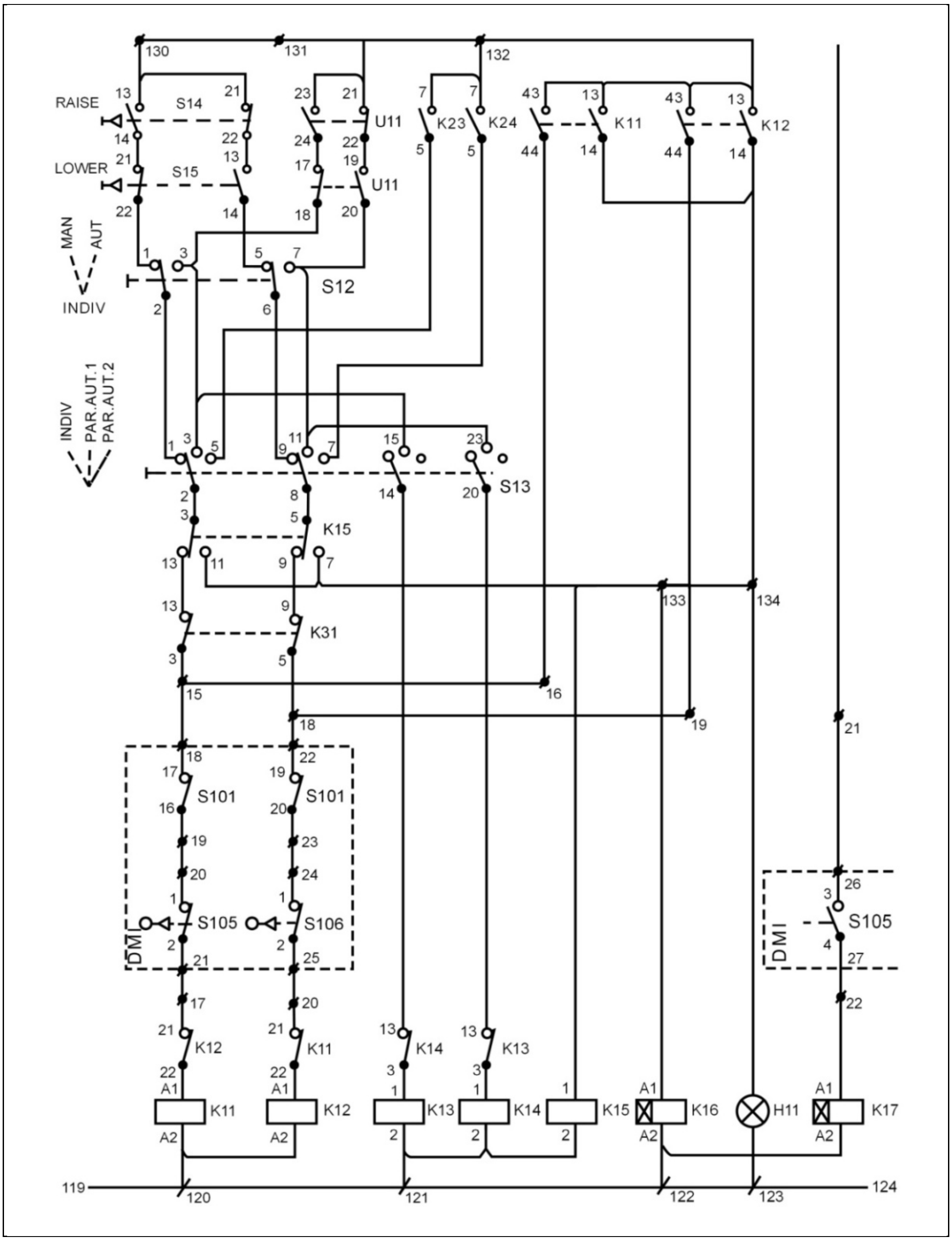


Fig. 1.2-8 Schematic Diagram for Tap Changer Controller

S_{14}, S_{15}: Pushbuttons to raise or lower tap changer

S_{12}, S_{13}: Selector Switches

K_{16}: Time delay relay for “tap changer failure”

K_{17}: Time delay relay for “Switching Time too long”

DMI: Driver Mechanism

SUMMARY

- Tap-changer in the power transformer is used to regulate and compensate for the fluctuation of line voltage due to loading.
- No-load or manual tap-changer is used for distribution and small power transformer.
- Tap-changer exists in the high voltage side of the transformer winding.
- Automatic tap changers are used for large power transformers and for voltage regulators.
- The tap selector switch is used to engage the tap connections on the tapped winding.
- The load transfer switch is a device by which the load current is transferred from one tap to the next after a tap change has been initiated.
- The resistors or reactors are employed as impedance to limit the circulating current developed when the taps during the on-load tap-changer's operation.
- Tap-changer controller senses the line voltage to be regulated, and determine the tap position.

GLOSSARY

No-Load:	With transformer de-energize
On-Load:	With connected load
Bypass Switch:	Redirect the current to another parallel pass
Selector Switch:	Select one circuit or the other for the passing current
Regulation:	Organization and control the operation
Mechanism:	Interlinked mechanical parts working together
Reactor:	Copper coil wound on a core
Diverter switch:	Load transfer switch
OLTC:	On-Load Tap Changer

REVIEW EXERCISE

Select the suitable answer and follow the other questions:

1. **Off-load tap-changer is used with:**

   a) Loaded power transformers. b) Control transformers.

   c) Distribution transformers. d) Large transformers.

2. **A transformer equipped with a no-load tap changer must always be ___________ to/from the circuit before the ratio adjustment can be made.**

   a) Connected b) Disconnected

3. **A transformer equipped with on-load tap changer may not be ___________ from the circuit before the ratio adjustment can be made.**

4. **An automatic transformer tap-changer is driven by a motor through**

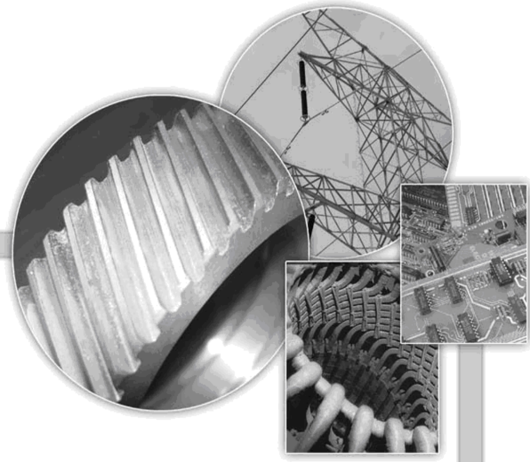
   a) A controller. b) An auxiliary relay.

   c) A timer. d) A pushbutton.

5. **The tap-changer controller is used to:**

6. **The main elements of the tap changer are:**

7. **The diverter reactors are used in the tap-changer to:**



LESSON 1.3

CURRENT TRANSFORMERS & PRIMARY INJECTION TEST SET

LESSON 1.3
CURRENT TRANSFORMERS & PRIMARY INJECTION TEST SET

OVERVIEW

This lesson explains the importance of current transformers (CTs) in the protection and measurements emphasizing on the safety precautions, burden, polarity, and how to test it using primary injection test set.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Identify the types of CTs and explain characteristics of current transformers.
- Calculate current transformer burden.
- Test current transformer.
- Illustrate the (Multi-Amp) primary injection test set.

Task 1.3-1: Polarity of current transformer
Task 1.3-2: Turns ratio test using primary injection test set
Task 1.3-3: Magnetization curve of current transformer

INTRODUCTION

Direct operation with heavy currents for the purpose of measurements or protection, would involve bulky and expensive instruments and relays in a wide variety of designs. Instrument transformers make it possible to use relatively small and inexpensive instruments and control devices of standardized design. Such transformers also isolate and protect the operator, the measuring devices, and the control equipment from hazards of high voltage or heavy current. Their use results in increased safety, accuracy, and stability for the power system. The two types of instrument transformers are voltage transformers (VTs) and current transformers (CTs).

CURRENT TRANSFORMER (CT)

A practical method to measure current in HV circuits is using current transformer. CT like any transformer consists of primary winding, secondary windings, and core. Primary winding is represented by one turn coil or the main conductor itself. The secondary winding transfers a small image of the primary winding carrying the actual power system current under normal or fault conditions.

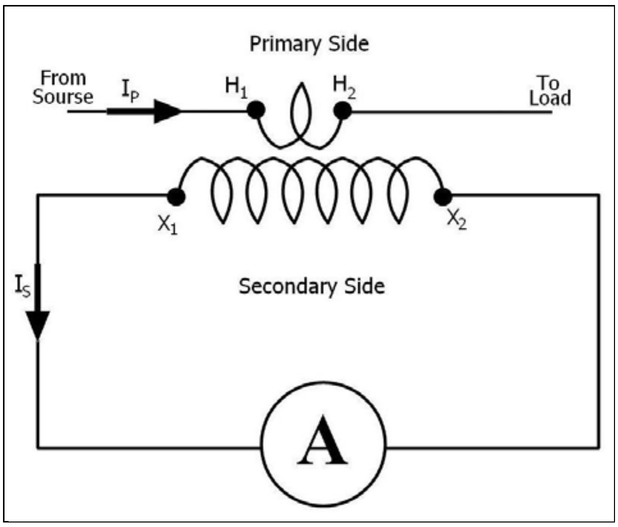


Fig. 1.3-1 Current Transformer

The primary winding is connected in series with the power circuit in which the current is to be measured, as shown in Fig. 1.3-1. The secondary winding supplies current usually 5 amperes or one ampere as standard for power system depending on the distance between switchgear and control room which affect the CT burden and the voltage drop The construction of current transformer in general follows the requirements of the applications to use the suitable core made of ferrite material, which is magnetized by current in the primary winding. Insulation appropriate for the system voltage is used between primary winding, CT core and secondary winding.

CONSTRUCTION OF CURRENT TRANSFORMER

Current transformers are divided into two main types - indoor and outdoor types.

INDOOR CURRENT TRANSFORMERS

Indoor or switchboard type transformers are used in the high, medium, and low voltage general purpose applications for protection and measurements. There are two classes of indoor current transformers - the first class includes **bar and wound primary types**, the bar type in which primary is represented by one turn (Fig. 1.3-2) or wound primary type in which primary is represented by a coil having some turns as shown in Fig.1.3-3 & 1.3-4.

The other class is called ring type (window or Toroidal) it is not equipped with primary winding. It consists of secondary winding and core as shown in Fig. 1.3-4.

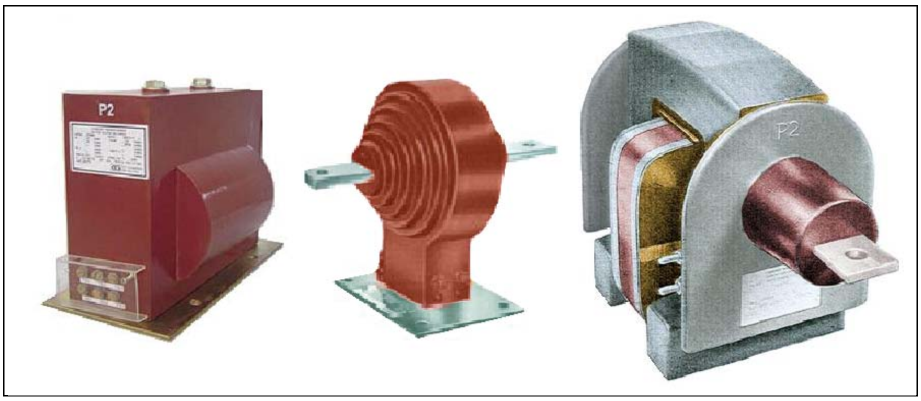


Fig. 1.3-2 Bar Type Indoor CTs

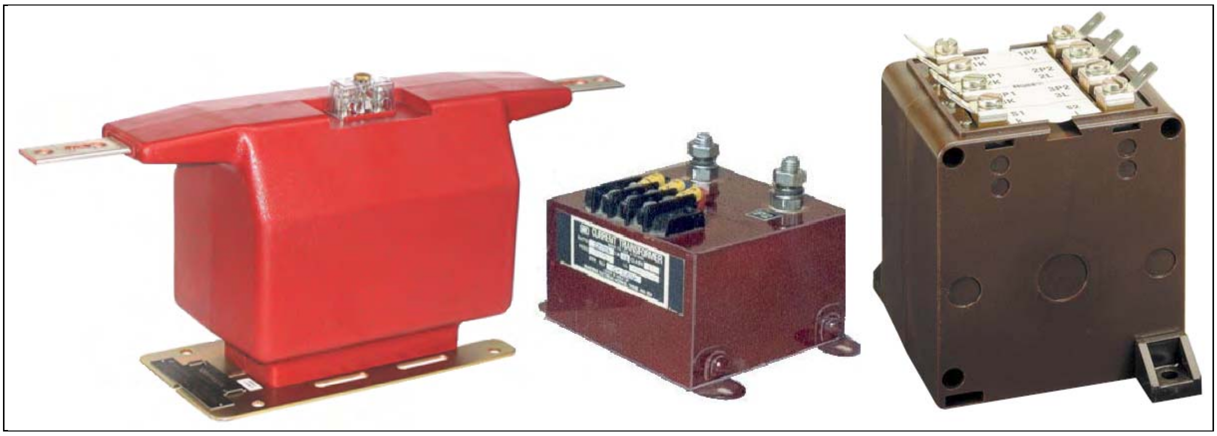


Fig. 1.3-3 Wound Primary Type Indoor CTs

Fig. 1.3-4 Ring Type Current Transformer

CT could be in a single or double core forms, as shown in Fig. 1.3-5 using a bar as the primary winding having one turn only and secondary having large number of turns.

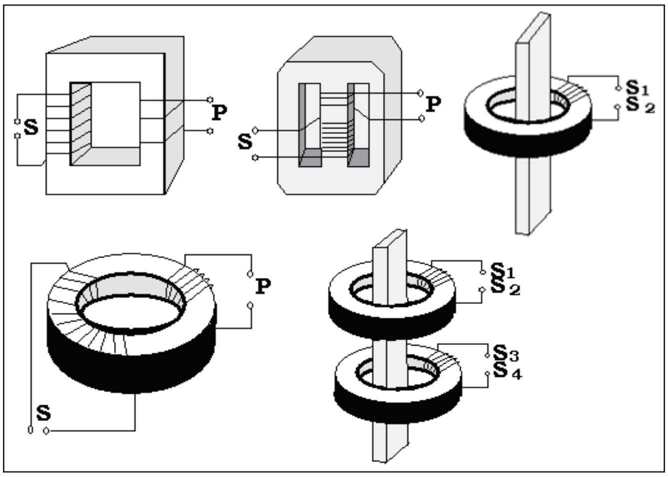


Fig. 1.3-5 Single and double core CTs

OUTDOOR CURRENT TRANSFORMERS

Outdoor current transformers are commonly constructed, as shown in Fig. 1.3-6. The core and coil are immersed in oil inside insolated bushing. These bushings may be long or short depending on the rated voltage the difference in construction is due to the requirement that the transformers be weatherproof.

Fig. 1.3-6 Bushing type oil immersed outdoor CTs

For high voltages, separately mounted post-type outdoor CTs are used in conjunction with HV Circuit Breakers, for example. The core and secondary windings are contained in an earthed tank at the base of a porcelain insulator and the leads of the full-insulated primary winding are taken up to the top helmet through the porcelain insulator. The insulation material of such current transformers is usually oil-impregnated paper. Another method for insulation employs a gas such as SF6.

MULTIPLE-SECONDARY CURRENT TRANSFORMERS

Current transformer secondary is often divided into separate multiple windings terminated in an output terminal box of the CT designated with standard symbols, as shown in Fig. 1.3-7. The separate multiple secondary windings supply the output secondary currents to operate many devices with different current requirements at the same time.

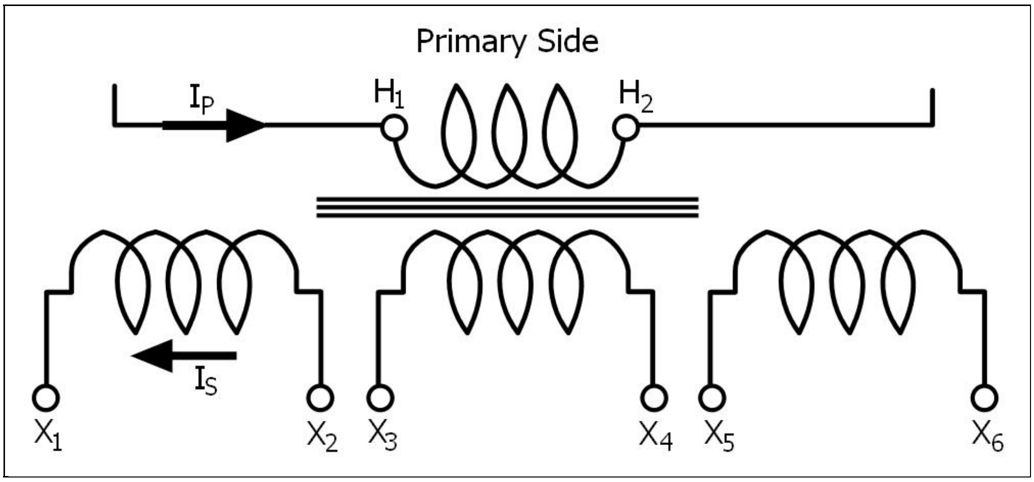


Fig. 1.3-7 Multi-Secondary Current Transformer

CURRENT TRANSFORMER BURDEN

Current transformer secondary is loaded with measuring or protective devices, called CT burden, as shown in Fig. 1.3-8. Each CT can be loaded with many devices in series. As more devices are added in series, the secondary current (I_S) of the CT decreases, resulting in increasing the magnetization current (I_M) leading to more losses and it leads to earlier saturation and inaccuracy. Equation (1) describes the current distributed in the CT.

$$\mathbf{(I_P /N) = I_S + I_M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)}$$

Where: I_P = Primary current.

N = Turns ratio.

I_S = Secondary current.

I_M = Magnetization current.

BURDEN IMPEDANCE (Z_B)

It is the maximum impedance connected in the secondary side without bad loading effect on the current transformer.

LOAD IMPEDANCE (Z_L)

It is the total actual impedance of the protective or measuring devices connected in series with the CT secondary including the connector impedances. For optimum operation of the CT to avoid any loading problems, $Z_B \geq Z_L$

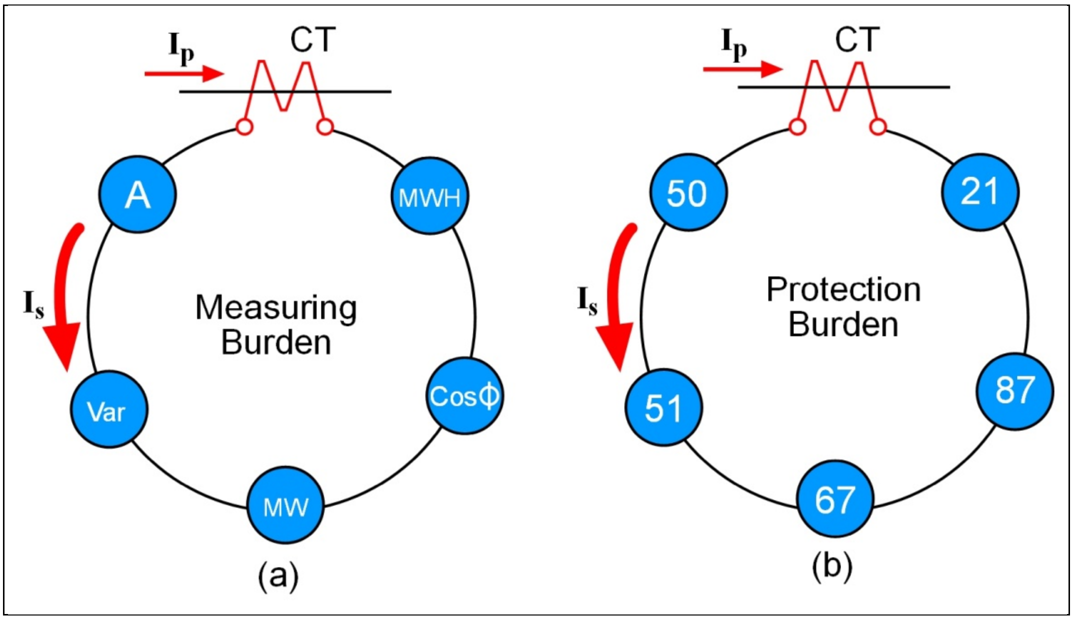


Fig. 1.3-8 CT Burden for Measuring and Protection

Measuring burden of CT	**Protection burden of CT**
A: Ammeter	50: Over current relay
Var: Reactive power meter	51: Over current with time delay
MW: Mega-watt meter	67: Directional over current relay
Cos ϕ: Power factor meter	87: Differential relay
MWH: Mega-watt hour meter	21: Distance relay

If Z_L is greater than Z_B, it increases the losses and overheating of the core, resulting in CT insulation damage.

The left side of equation (1) (I_P /N) is a constant value in most cases. Any decrease in secondary current due to increasing load resistance (by adding more devices) result in increase in the magnetization current and early core saturation.

The burden impedance (Z_B) of the CT is calculated from equation (2).

$$\mathbf{Z_B = VA / (I_S)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathbf{(2)}$$

Where: Z_B = burden impedance.

VA = current transformer capacity (burden).

EXAMPLE 1.3-1

A protection CT has a secondary current of 5A and rated capacity of 30VA. It is required to connect the CT secondary with three protective relays. Their current coils' impedances are as follows: 0.4Ω, 0.7Ω, 0.3Ω, and connectors' impedances of 0.2Ω. Calculate the maximum burden impedance for the CT, and determine if the CT can operate satisfactory with these relays or not.

SOLUTION

Burden impedance of the CT; $Z_B = VA / (I_S)^2 = 30 / (5)^2 = 1.2\Omega$

The total load impedance of the CT; $Z_L = 0.4 + 0.7 + 0.3 + 0.2 = 1.6\Omega$

It is obvious that burden impedance Z_B is less than load impedance Z_L, so in this case, the CT operation will not be satisfactory due to loading effect.

CURRENT TRANSFORMER ACCURACY (ANSI STANDARD)

The ANSI CT accuracy class is based on the steady-state performance. The secondary terminal voltage rating is the CT secondary voltage that the CT will deliver when it is

connected to a standard secondary burden, at 20 time's rated secondary current, without exceeding a 10% ratio error. For example, CT accuracy class C100 means that the ratio error will not exceed 10% at any current from 1 to 20 times rated secondary current with a standard 1.0 Ω burden (1.0 Ω times 20 times rated secondary current equals 100 V). The C or K classification covers almost all of the CTs used for protective relay applications, including bushing CTs with uniformly distributed windings, and other CTs with minimal core leakage flux.

The letter designation codes are, as follows:

C: It indicates that the leakage flux is negligible.

K: It is the same as the C rating, but the knee-point voltage must be at least 70% of the secondary terminal voltage rating.

T: Test determines the ratio error. The T class CT has the flux leakage effect in the core.

H, L: These are old ANSI classifications. There were two accuracy classes 2.5% and 10%. CTs were specified in the following manner 10 L 200, 2.5 H 400, etc. The first number (10) indicates the accuracy class and the last number indicates the secondary voltage class. L-CTs were rated at specified burden and at 20 times normal current whereas H-CTs were rated at any combination of burden from 5 times to 20 times the normal current. These ratings are applicable only to old CTs.

CURRENT TRANSFORMER ACCURACY (IEC STANDARD)

IEC standard covers the general requirements applicable to all CTs and covers the additional requirements of the protective, Class P. The accuracy requirement of this class of CT is similar to the ANSI Class T. Four other protective CT classifications are defined for CTs and cover the transient performance in considerable detail. This is referred as TP classification. The following is a brief summary of the IEC methods of classifying protective CT accuracy.

a) Accuracy of the IEC Class P Current Transformers

The accuracy limits for Class P CTs are defined with symmetrical primary current in terms of maximum composite error at a specified multiple of the rated current with a specified burden in VA **(S_b)**. The procedure and the syntax are illustrated by showing how an ANSI **T400** CT would be designated in IEC terminology.

IEEE Standard classifies protection CTs with a specified secondary terminal voltage across standard impedance **(Z_B)**. The accuracy class rated voltage is measured with 20 time's rated steady-state symmetrical current, and the limit of acceptable composite ratio error is 10% For example, a CT with ANSI accuracy classification **T400** would be 100 VA, 10P20 in IEC terminology :

ANSI - T400 ≡ IEC - 100 VA, Class 10P20

$Z_B = V_{acr} / 20\ I_n = 400/100 = 4\Omega$ when $I_n = 5A$

Where:

$S_b = Z_B \times (I_n)^2 = 100$ VA

10: 10% composite error limit

P: Protection CT

20: Accuracy limit factor (20 times the rated current)

The standard IEC values for the error limit are 5 or 10. Standard values for the accuracy limit factors are 5, 10, 15, 20, and 30.

b) Accuracy of the IEC Class TP Current Transformers

There are four different TP classifications to meet different functional requirements as follows:

- Class TPS low leakage flux design CT
- Class TPX closed core CT for specified transient duty cycle
- Class TPY gapped (low residual magnetic flux) CT for specified transient duty cycle

- TPZ linear CT (no residual magnetic flux)

The error limit for TPS CT in terms of turn ratio error is ±0.25% and the excitation voltage under limiting conditions should not be less than the specified value. Furthermore, this value is such that an increase of 10% in magnitude does not result in an increase in the corresponding peak instantaneous exciting current exceeding 100%. In other words, the CT should not be in saturated state at the specified maximum operating voltage. For TPX, TPY, and TPZ transformers, the error limit is summarized in the table below.

Class	**At rated Current**		**At accuracy limit condition**
	Ratio Error %	**Phase displacement minimum**	**Peak instantaneous Error** %
TPX	±0.5	±30	10
TPY	±1.0	±60	10
TPZ	±1.0	180 ± 18	10 *

* Alternating current component error

ERROR MEASUREMENTS

The error measurement is carried out by using two ammeters. One is connected to measure the primary current and the other to measure secondary current, as shown in Fig. 1.3-9 then calculating % RE.

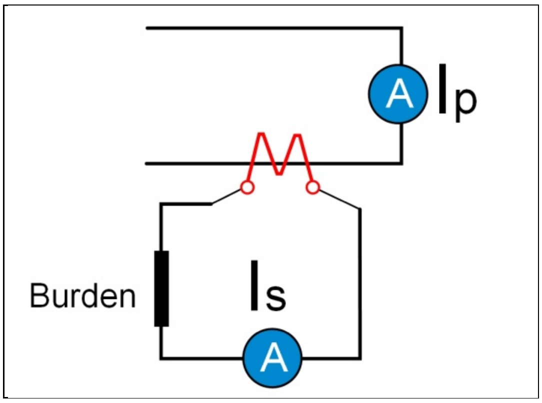
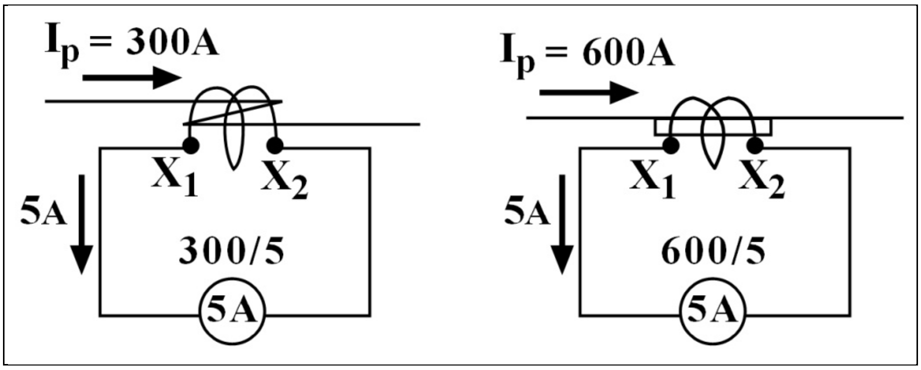


Fig. 1.3-9 Direct Testing of CT

CHANGING TURNS RATIO ON PRIMARY WINDING

The primary circuit consists of two bus bars or windings that may be connected in series or parallel to give the two required ratios, (Fig. 1.3-10a, & b). Assume that the same CT of Fig. 1.3-10 is used with two different primary currents 300A and 600A, respectively. As shown, the ratio of the CT is 300/5. By re-arranging the primary connections, as shown, the ratio of the CT becomes 600/5.



(a) Series primary bus (b) Parallel primary bus

Fig. 1.3-10 Changing Turns Ratio from Primary Side

CHANGING TURNS RATIO ON SECONDARY WINDING

Assume the ratio of CT is 1000/500:5 is required. Secondary terminals X_1-X_3 are used to give turns ratio of 1000:5. Secondary terminals X_1-X_2 are used to give turns ratio of 500:5 (Fig. 1.3-11).

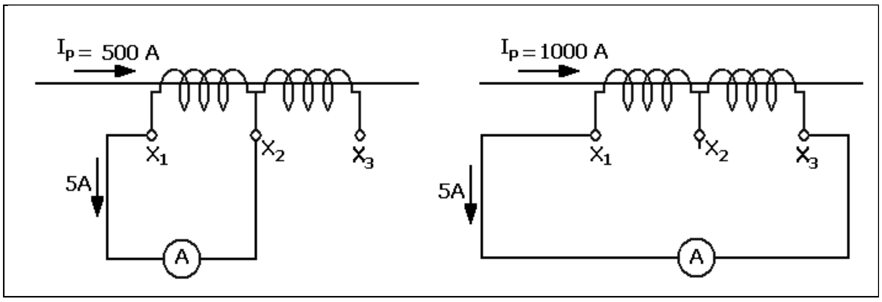


Fig. 1.3-11 CT with Taped Secondary

MEASURING AND PROTECTION CORES

Bushing Current transformer for high voltage applications has often multiple secondary windings wound on separate cores each with different core characteristics for protection and measurement.

MEASURING CORE

For normal operation, it has high accuracy, low errors and steep saturation (very low magnetization curve) when overcurrent or fault occurs. The core material is made of grain oriented hot rolled silicon steel.

PROTECTION CORE

For normal operation, it has low accuracy, and no saturation (very high magnetization curve) when overcurrent or fault occurs. The core material is made of cold rolled oriented silicon steel.

TWO CORE CT FOR DIFFERENT VA BURDEN

Fig. 1.3-12 shows the schematic diagram for the current transformer with two different cores, one for measuring and other for protection purposes.

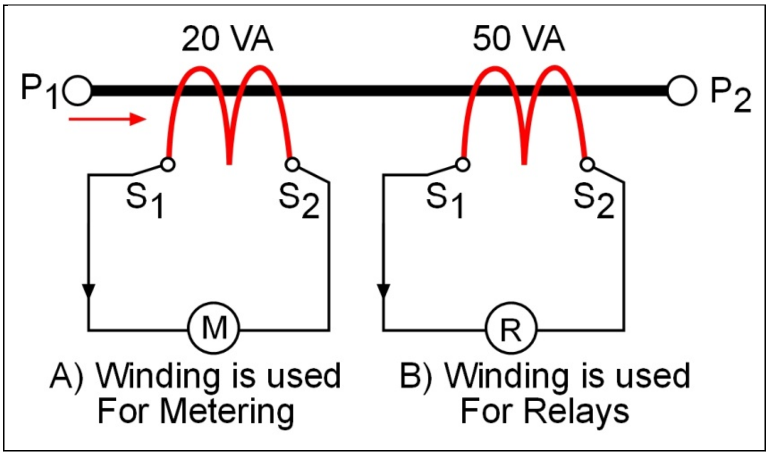


Fig. 1.3-12 Measuring and Protection Core in bushing Type Current Transformer

MAGNETIZATION CHARACTERISTIC CURVES

The magnetization characteristic of CT depends on the cross-sectional area, core material, and length of the magnetic path. Fig. 1.3-13 shows typical magnetization curve for cold rolled oriented Silicon steel. The curve shows typical relationship between secondary emf and exciting current. The point K_P on the curve is called the knee-point where saturation begins and is defined as the point at which an increase of 10% in the exciting emf produces an increase of 50% in the exciting current.

Magnetization curve is the relationship between magnetizing force (H) or ampere turns/mm and flux density (B). The curve is divided into two parts, the knee point at K_P dividing the linear and non-linear (exponential) regions. The lower part is extremely linear area for normal operation. The upper part is extremely flat and is not recommended. It is the worst area for operation.

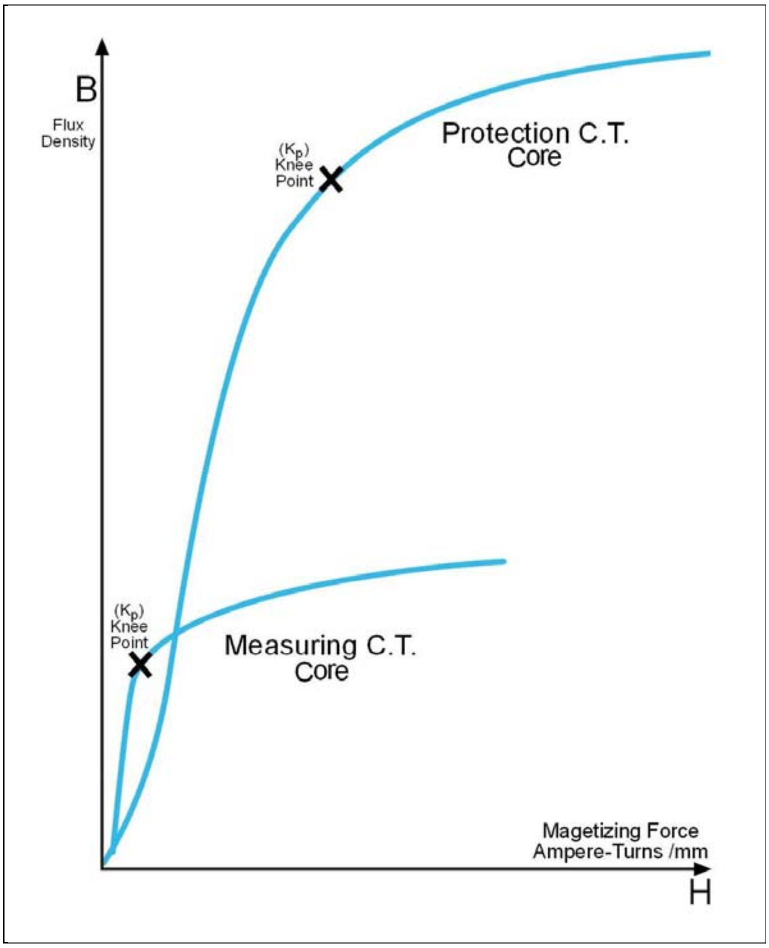


Fig. 1.3-13 Magnetizing Curve for CT Turns-Ratio 500/1 with SEC resistance 2

The protective current transformer core has very long lower liner area and small upper flat area, as shown in Fig. 1.3-13. On the other hand, the measuring current transformer core has small lower linear area and long upper flat area.

CAUTION

The secondary circuit of current transformers must be continuously closed either by instruments or relays connected in series with it or else by a metallic band when the primary circuit has current flowing through it.

If the secondary circuit is open-circuited with primary current flowing, there is no secondary emf to oppose and all the primary emf acts on the core as a magnetizing quantity. If the current is appreciable, the core is driven into saturation on each half wave and hence the high rate of change of flux. While the primary current passes

through zero reference, it induces a high peak emf in the secondary winding. With rated primary current flowing, this emf may be a few hundred volts for a small CT but many kilovolts for a large high ratio protective CT. With system fault current flowing, the voltage would be raised in nearly direct proportion to the fault current value.

Such voltages are dangerous not only to the insulation of the CT and connected apparatus, but more importantly, to human life. This condition must be avoided. If the secondary circuit has to be disconnected while primary current is flowing, it is essential first to short-circuit the secondary terminal of the CT. The conductor used for this purpose must have adequate rating to carry the secondary current and should be securely connected, including the worst case current that would flow if a primary system fault occurs.

CURRENT TRANSFORMER CONNECTIONS

Current transformers can be connected in different configurations depending on specific applications. The connections and polarity relationships are even more critical when current transformers are used to supply informational input to most of protective relays, watt-hour meters, and other recording and measuring devices. The most commonly used current transformer connections are the star (WYE) connection, delta (Δ) connection, open-delta connection, the transformer connections, and the polarity identifications are illustrated for various protective schemes (Fig. 1.3-14 to 1.3-17).

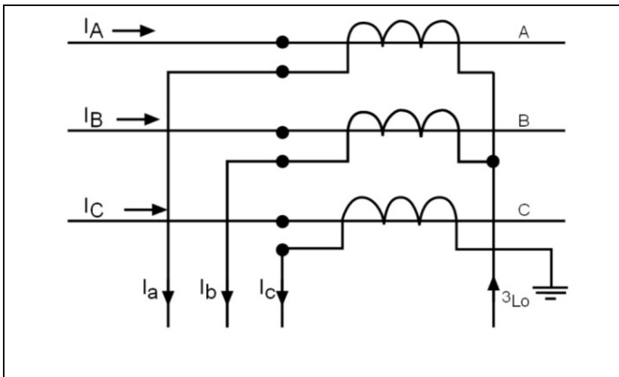


Fig. 1.3-14 Star (Wye) Connection

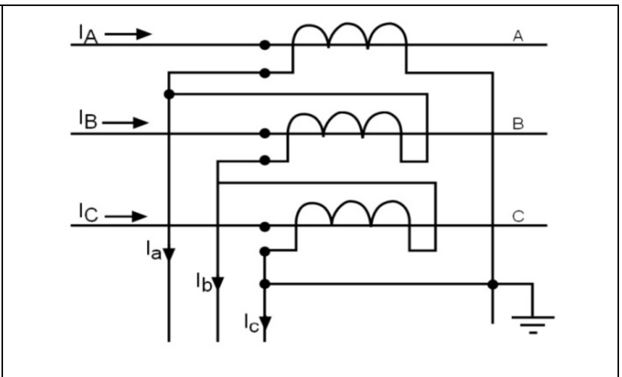


Fig. 1.3-15 Delta Connection

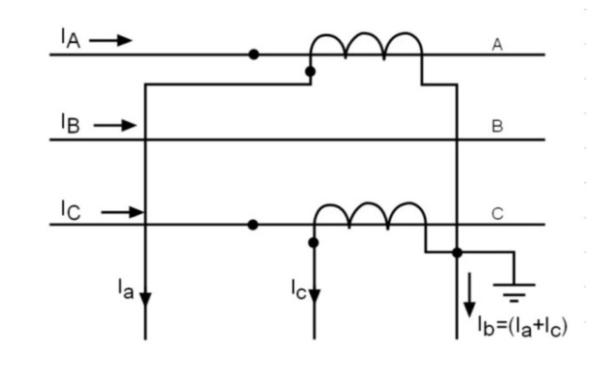


Fig. 1.3-16 Open Delta (V) Connection

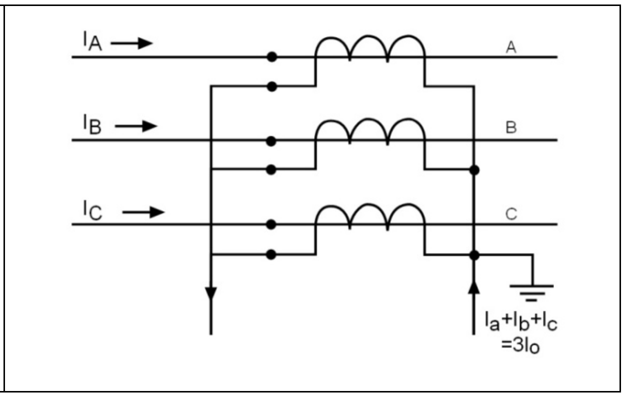


Fig. 1.3-17 Zero-Sequence (Residual) Connection

CURRENT TRANSFORMER TESTING

A current transformer is tested for four basic characteristics: insulation resistance, turns ratio, polarity, and saturation.

INSULATION TEST

Insulation tests are performed by applying HV to one end of the primary or secondary winding for a short time, the other end being connected to the frame and earth, and all other windings being short-circuited. The test voltage for secondary windings is 2kV, while that for primary windings depends on the rated primary voltage of the CT. Bar-type CTs are tested winding-to-winding (bar) and winding-to-ground using a 500 volt DC megger.

TURNS RATIO TEST

This method utilizes heavy cable and some type of current source such as a generator or a low-voltage, high-current test set, (Fig. 1.3-18). The high current source (primary injection test set) passes full load rated current into the primary of the CT, if possible, and measuring the amperage on the secondary.

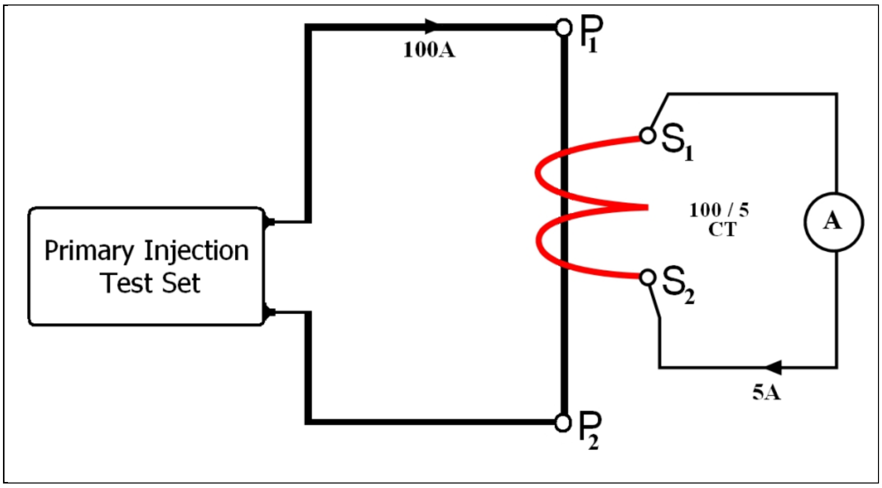


Fig. 1.3-18 Turns Ratio Test

The primary hazard that may be encountered if the secondary circuit may open while under load, results in a shock and/or body injury or even death. As long as the secondary circuit is closed, a counter-magneto-motive force (CMMF), proportional to the current in the primary, is produced in the secondary. The primary of a current transformer has few turns and its impedance is small, even when the secondary is open. As a result, the primary current changes little if the secondary current is opened, accidentally. However, there is no longer a secondary MMF in opposition to that of the primary. This results in a high secondary voltage. Therefore, the secondary of a current transformer should always be kept closed, even if it is sitting on a shelf.

POLARITY TEST

Current transformer polarity, as shown in Fig. 1.3-19 is necessary for directional, differential and distance protection applications. It is also important for some measuring applications like wattmeter, Var-meter, and watt-hour meter. As the instant current is flowing into the primary polarity mark, it is flowing out of the secondary polarity mark. A general rule for both potential and current transformer is to consider the secondary polarity mark a continuation of the primary polarity mark.

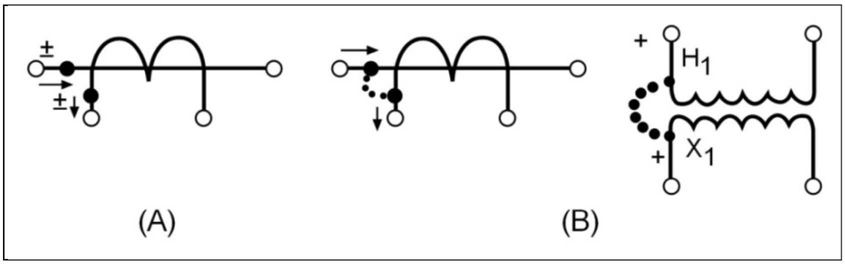


Fig. 1.3-19 Polarity

The best method of testing a current transformer for polarity is to follow the current (inductive kick) method. A 12 volt battery is connected to the primary of the CT through a switch and a conductor. A DC milli ammeter is connected to the secondary with polarities, as shown in Fig. 1.3-20. The switch is momentarily closed. If the polarity of the current transformer is properly marked, the mille-ammeter will rise slightly above zero, drop below zero and then return to zero.

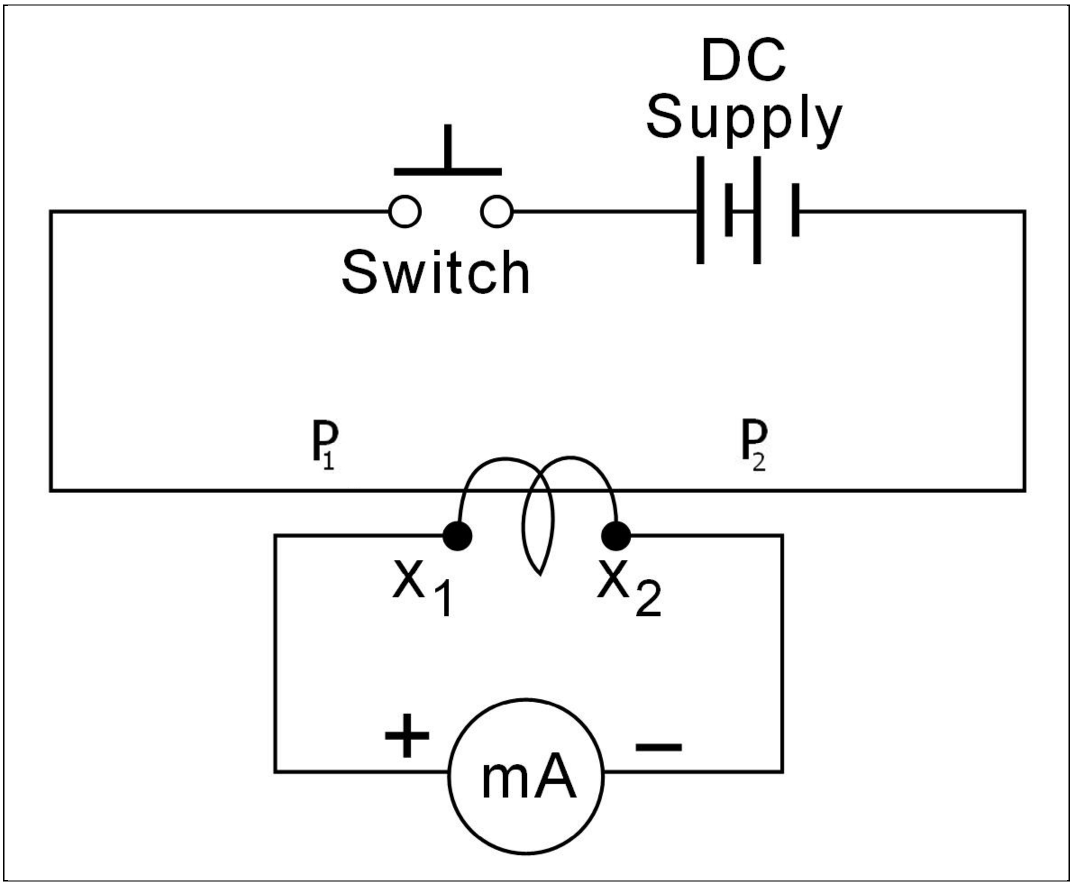


Fig. 1.3-20 Polarity Test Using DC Supply

POLARITY TEST BY COMPARING WITH A CT OF UNKNOWN POLARITY

An alternative test, called comparator method, utilizes two CTs in circuit with same turn's ratio. The secondary winding of one CT with known polarity is connected in series with the secondary winding of the other CT with unknown polarity, as shown in Fig. 1.3-21. If ammeter reads 0 Ampere, the polarity of unknown is as indicated. If ammeter reads 10 Amperes, the polarity of unknown is reversed.

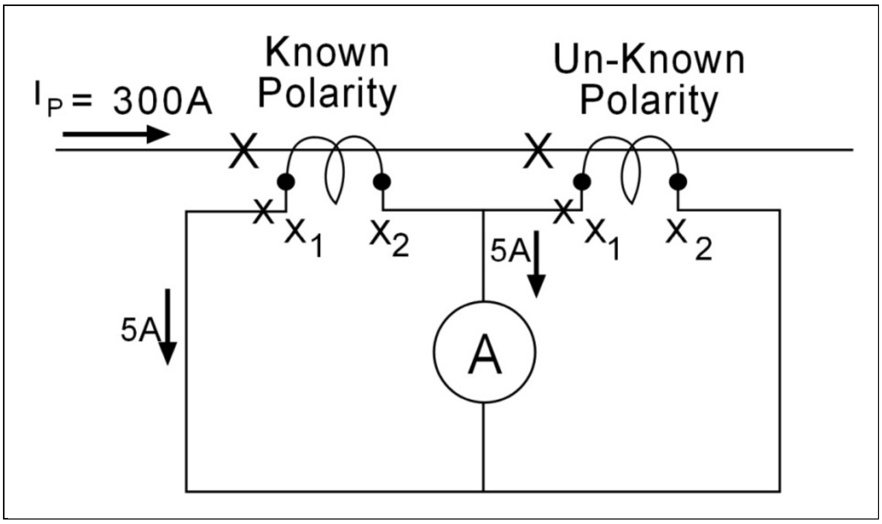


Fig. 1.3-21 Polarity Test Using known Polarity CT

SATURATION TEST

The saturation test is applied to check the core health of the CT core for either measuring or protection application. The saturation for the CT means that the core becomes unable to transfer magnetic field (totally or partially) to develop the secondary current, proportionally, due to residual flux.

SATURATION REASONS

1- Open secondary circuit
2- Loading burden is more than CT rated burden

3- Abnormal heavy fault current

Saturation test is applied, as shown in Fig. 1.3-22, (see Task 1.3-3 for more details).

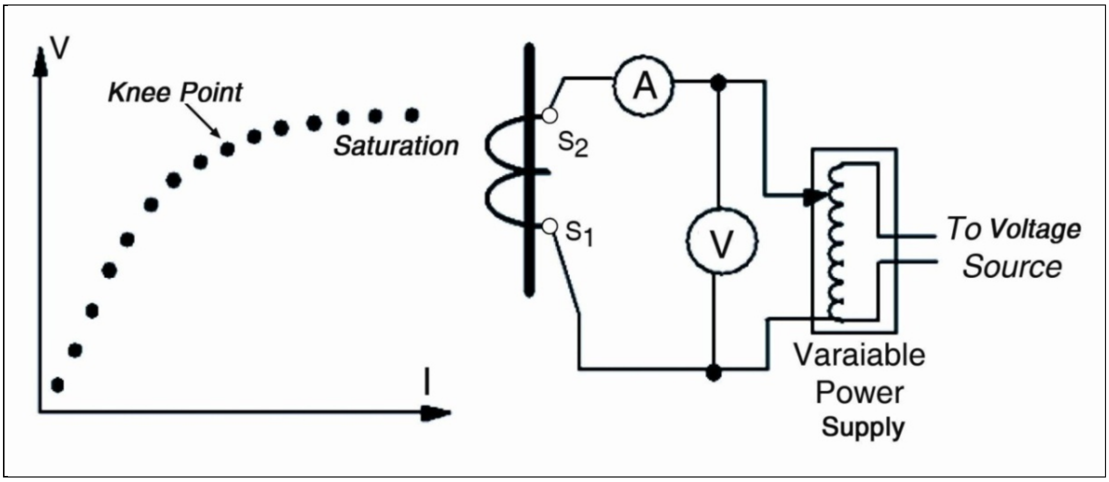


Fig. 1.3-22 Saturation Test

CURRENT TRANSFORMER FOR DIGITAL RELAYS

Most electromechanical relays have relatively high resistance current coil, which add high burden on the CT secondary. In the case of digital relays, a matching circuit, called Rogowski coil, is used at the relay input (Fig. 1.3-23 & 1.3-24).

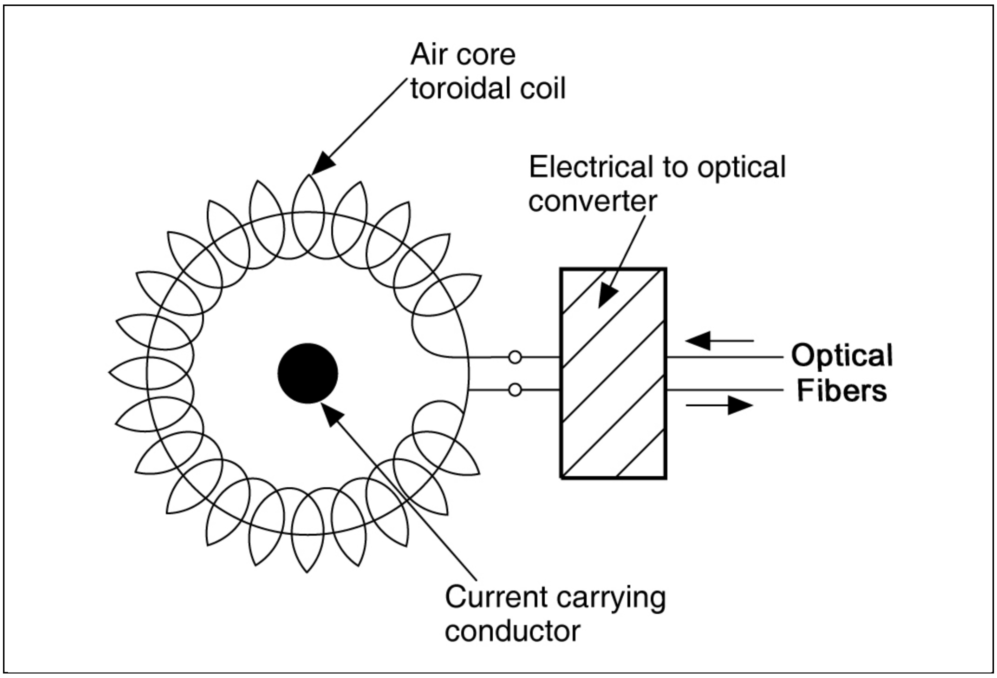


Fig. 1.3-23 Schematic Representation of a Rogowski Coil, used for current sensing

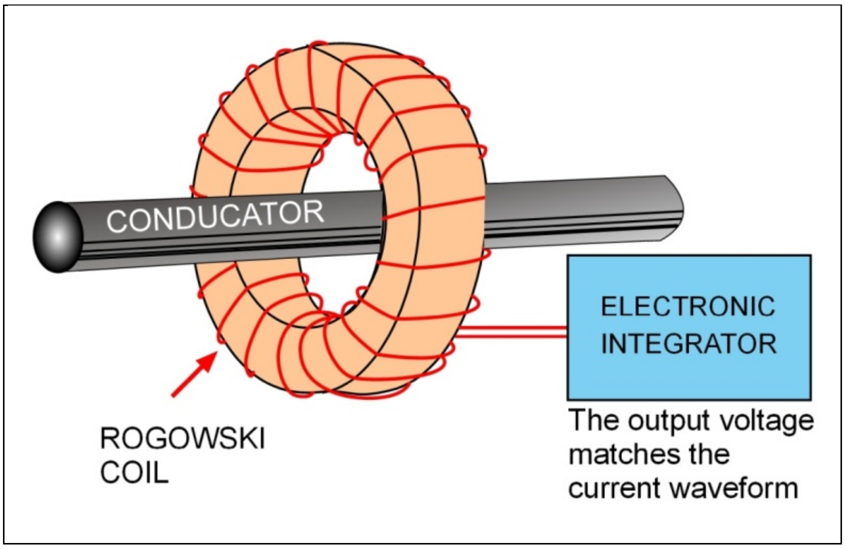


Fig. 1.3-24 Rogowski Coil

A Rogowski coil is a circular Toroidal coil placed round the conductor. The alternating magnetic field produced by the current induces a voltage in the coil proportional to the rate of change of current. The combination of a coil and an integrator provides an excellent current measuring circuit to accommodate an accurate phase response in measuring complex current waveforms and transients.

SUMMARY

- Current transformer is used to decrease current from kilo amperes to a few amperes and isolate instrument/device from high voltage.
- Primary winding of CT is the power line conductor with one turn winding.
- There are two types of CT applications: Measuring and protection.
- The burden of the CT is calculated for all devices and connectors impedances that can be connected in series with the secondary.
- The used megger for insulation test is selected with a voltage suitable for the current transformer.
- Polarity test of CT depends on the transient current from the DC supply by momentarily pressing and opening the switch.

- The percentage Ratio Error increases with primary current above the knee point.
- Turns ratio test is applied by primary injection test unit and monitoring secondary current on an ammeter.

FORMULAE

$S_b = Z_B \times (I_n)^2$

Where: S_b: Max. Volt-Ampere of CT

Z_B: Burden impedance

I_n: Nominal secondary current

$Z_B = (VA) / (I_S)^2$

Where: Z_B : Burden impedance.

VA : Current transformer capacity.

I_S secondary current of the CT.

GLOSSARY

Transient moment:	The first few millisecond of switching a circuit
Primary injection:	Inserting high current from primary side
Megger:	A device used for insulation test
Outdoor:	A device located outside in the open air/switchyard
Indoor:	A device is located inside a closed building
Knee point:	A point on the CT characteristic that determines saturation
CT burden:	The max. load to be connected to CT secondary
CT accuracy:	Accurate degree for transfer ratio
Saturation:	A property of the core filled with magnetic field
Flux density:	Amount of magnetic field per square centimeter
Multi-Amp:	The manufacturer of the primary test set used
TP Class:	Transient Performance class for CTs.
Toroidal coil:	Ring coil.

REVIEW EXERCISE

I) Select the correct answers:

1. The burden devices of the current transformer are connected:
   - a) Never mind connector resistance
   - b) In parallel
   - c) In series
   - d) In the primary side

2. The load impedance of the current transformer must be:
   - a) Equal to burden impedance
   - b) Greater than burden impedance
   - c) Never mind
   - d) Less than burden impedance

3. On a nameplate of CT, it was found 5P10; it means that:
   - a) The composite error limit is 10
   - b) Composite error is limit is 5%
   - c) The accuracy degree is 10
   - d) Rated secondary current is 5A

4. Saturation test is applied:
   - a) On the primary side
   - b) On the secondary side

5. Polarity test is necessary for CT that operates:
   - a) Overcurrent relay
   - b) Under voltage relay
   - c) Differential relay
   - d) Earth fault relay

6. The B-H curve of the measuring current transformer core is:
   - a) Higher than B-H curve of protection.
   - b) Lower than B-H curve of protection.
   - c) The same level with B-H curve of protection.
   - d) Never mind which is higher.

II) Answer the following questions:

1. Draw a simple diagram of a CT connected to a power line.
2. Find the primary current of a CT, which has nameplate turns ratio of 2000/5. The secondary winding connected to an ammeter indicating 2 Amperes.
3. A current transformer has two separate secondary windings rated (300 - 600)/5, as shown in Fig. 1.3-25. Give a connection of the CT secondary windings with ammeter to read 5A if it is:

   a) Used for 300 amps. b) Used for 600 amps.

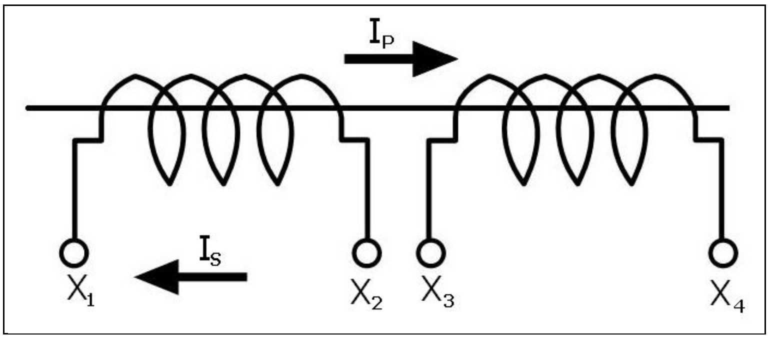


Fig. 1.3-25

4. What does the rating of 400/200/5 on a CT mean?
5. What is the normal rated current in the secondary of a CT?
6. Explain with the aid of drawing saturation of a CT core.
7. Explain with drawing, what polarity means.

III) Answer the following with true or false:

1. Turns ratio test is applied by DC source.
2. Load devices of current transformer are connected in parallel.
3. The energized CT secondary can be short circuit without loads.
4. Current transformer's primary is connected in parallel with the system.
5. Saturation test is applied by primary injection test set.
6. Standard CT secondary currents are 1 ampere or 5 amperes.

IV) A protection CT has a secondary current of 5A and rated capacity of 30VA. It is required to be connected with three relays, their current coils' impedances are 0.4Ω, 0.7Ω, 0.3Ω, and connectors of 0.2Ω. Calculate the maximum burden impedance for that CT, and show if the this CT can operate with these relays or not.

TASK 1.3-1

POLARITY OF CURRENT TRANSFORMER

OBJECTIVE

Upon completion of this task, the participants will be able to:

- Check the Polarity of current transformer.

TOOLS, EQUIPMENT AND MATERIALS

1 – Current transformer (any type)	1 - DC voltage source
1 – DC milli-ammeter	1 - Push button switch

NOTE

When closing the push button, the DC ammeter should give a positive flick and by opening the push button, the DC ammeter should give negative flick.

PROCEDURE

1. Receive from the instructor the following:
   - Current transformer to check its polarity
   - D.C. source 12V
   - Center scale pointer milli-ammeter
   - Push button switch
2. Connect the CT circuit, as shown in Fig. 1-1.

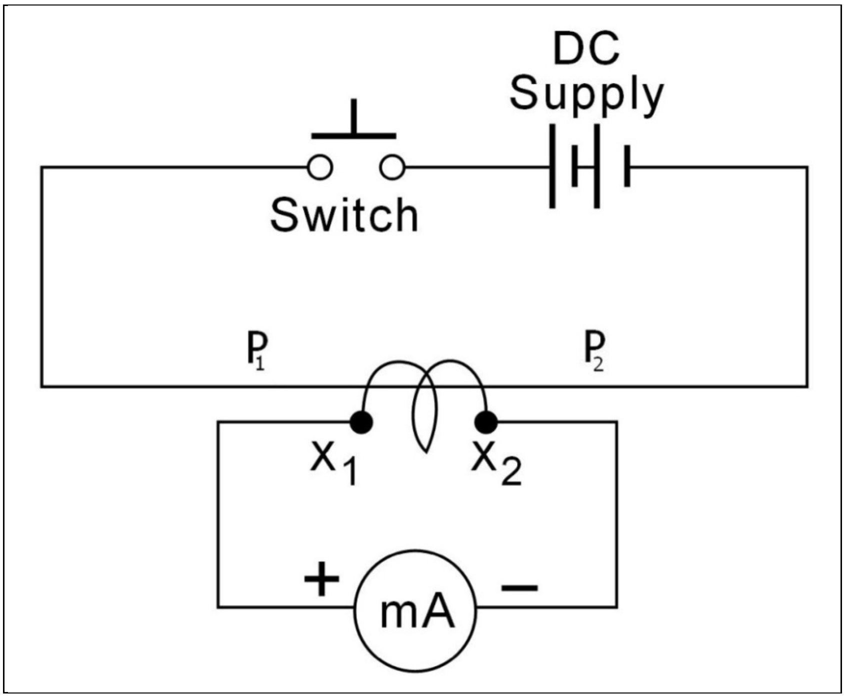


Fig. 1-1 Polarity Test Circuit

3. Press the push button switch and release it and monitor the pointer deflection.

4. The DC supply develops current in the primary circuit from left to the right direction, these results in secondary current passing in the CT from left to right. **True** or **False.**

5. This secondary signal is passing in the meter from left to right, so the pointer will deflect toward the left direction momentary and return to zero. **True** or **False.**

6. If the pointer deflects toward the right direction, then the polarity is reversed.
True or **False.**

TASK 1.3-2

TURNS RATIO TEST FOR CURRENT TRANSFORMER

OBJECTIVE

Upon completion of this task, the participants will be able to:

- Check the Turns Ratio of CT using primary injection test set.

TOOLS, EQUIPMENT AND MATERIALS

1 – Current transformer (any type)

1 – Primary injection test set unit

1 – AC Ammeter

PROCEDURE

1. Receive the following from the instructor:
    a. Window type CT to check its turn's ratio.
    b. AC ammeter.
    c. Multi-Amp. Primary injection test set.

Fig. 2-1 Primary Injection Test Set (Multi-amp)

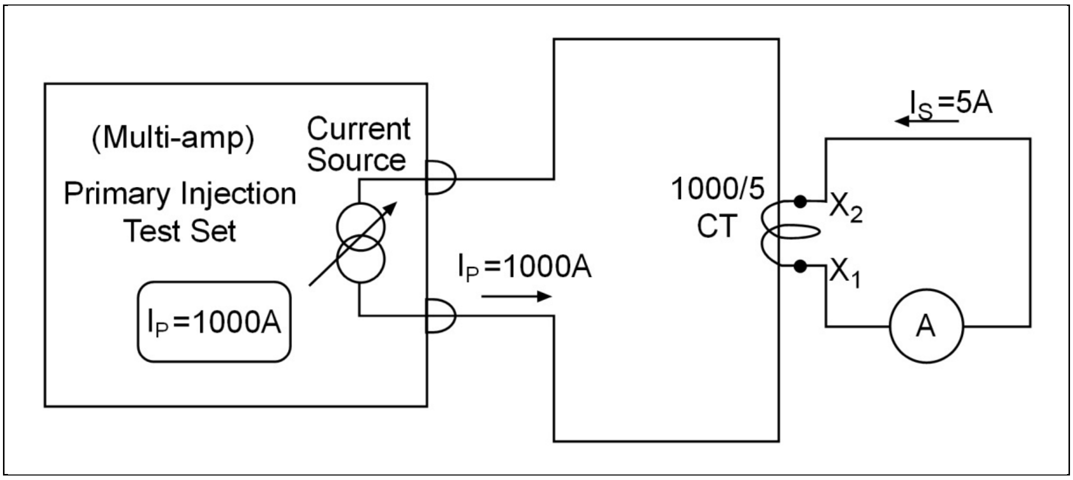


Fig. 2-2 Turns Ratio Test using Primary Injection Test Set

2. Connect the circuit, as shown in Fig. 2-2.

3. Adjust the plugs and switches on the front panel of the given tester to give output of 1000 amperes.

4. Adjust the control knob of the current source at zero output.

5. Switch on the test unit and slowly raise the output current until it indicates 1000 amperes if possible.

6. Record the reading of the AC ammeter.

7. Divide the produced primary current value of the tester by the measured secondary current value.

8. By apply turns ratio equation: T.R = I_P / I_S = …………….

9. Compare the turns ratio for CT terminals (X_1-X_2) with the nameplate.

10. Repeat the procedure for CT terminals X_1-X_3.

11. Record the turns ratio results, and compare the two results.

12. Decrease the current to zero, then shut down the primary injection test set.

TASK1.3-3

MAGNETIZATION CHARACTERISTIC CURVE OF CT

OBJECTIVE

Upon completion of this task, the participants will be able to:

- Perform magnetization curve plotting for protective current transformer.

TOOLS, EQUIPMENT & MATERIALS

1 – Protective CT (any type), rated secondary 5 amperes

1 - AC voltage source 1 – AC ammeter 1 – AC voltmeter

PROCEDURE

1. Receive from the instructor the following:
   a. AC ammeter
   b. AC voltmeter
   c. AC voltage source
   d. Current transformer of 5 Amp. rated secondary.

2. Inspect the materials and equipment for good condition.

3. Connect the variable voltage source (tester), ammeter, voltmeter, and the largest winding of CT secondary terminals X_1-X_3, as shown in Fig. 3-1.

4. Switch on the tester and slowly increase the voltage control knob in steps (0.5 volt per step).

5. Fill in the table with the corresponding current for each voltage increment.

6. Continue increasing the voltage with the current, until you find large increase in current occurs with small increase in voltage.

7. Stop increasing voltage and slowly decrease the voltage until you get zero voltage with zero current.

8. Monitor and review the result during decreasing the voltage, finding that the same measuring points are inversely reading again.

10. Any change in that reading will be due to residual magnetism that is unacceptable for the CT.

11. Return the voltage to zero and shut down the supply voltage.

12. Plot the results on the diagram shown in Fig. 3-2.

13. Determine the point at which the magnetizing current increases rapidly for a small increase of voltage.

14. Review and compare the old plot from the previous test with the new-plotted results.

15. The new plot result must be drawn on the previous test plot to determine if the CT has a problem.

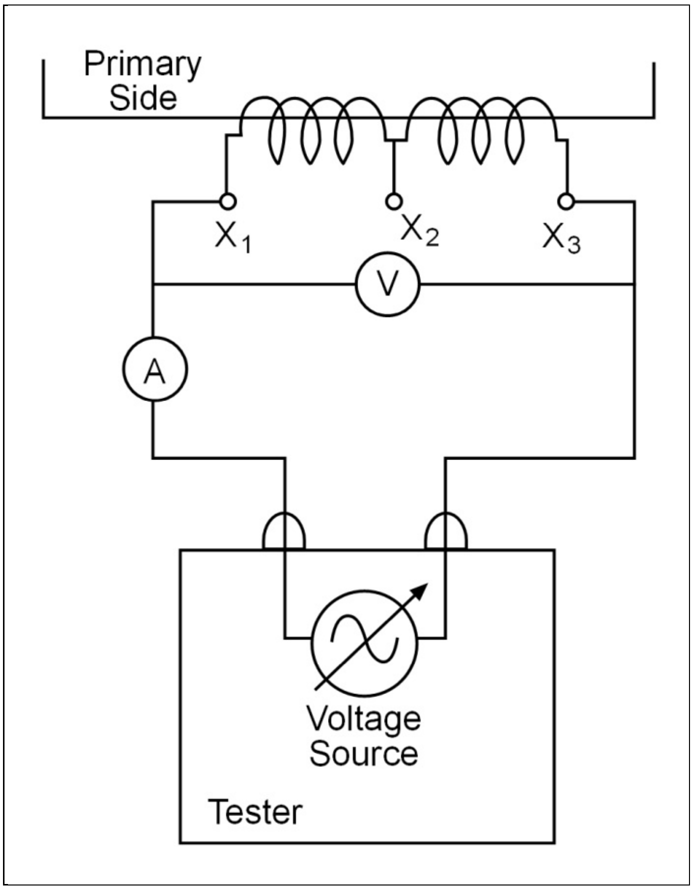


Fig. 3-1 CT Connection during Saturation Test

Voltage V	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Current mA																	

NOTE

All the connections must be made securely on the secondary side of the current transformer for safe operation of CT during the task.

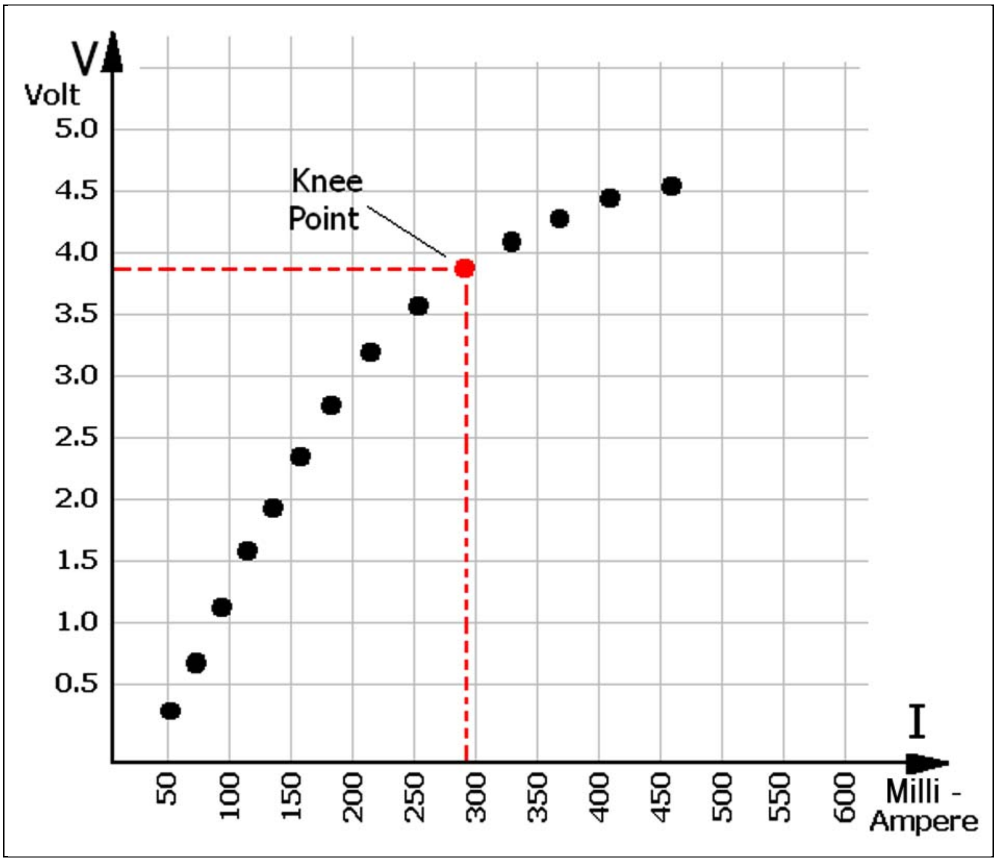
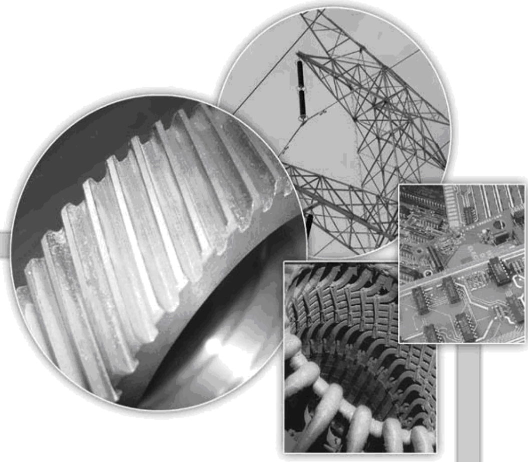


Fig. 3-2 Plotting Magnetization Curve of the CT



LESSON 1.4

VOLTAGE TRANSFORMERS

LESSON 1.4
VOLTAGE TRANSFORMERS

OVERVIEW

This lesson explains the importance of voltage transformers (VTs) in the protection and measurement applications emphasizing on the safety precautions, burden, and how to test it for insulation, polarity and turns ratio.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Identify the types of VTs and explain their characteristics.
- Calculate voltage transformer burden.
- Test voltage transformer.

Task 1.4-1: Inspect VT and read nameplate information.

INTRODUCTION

Direct operation with the high voltage requires voltage transformers, also called potential transformers, for the purpose of measurements or protection. That would involve bulky and expensive instruments and relays in a wide variety of power applications. Voltage transformers make possible the use of relatively small inexpensive standard instruments and control devices available from the manufactures. Such transformers (Fig. 1.4-1) also isolate and protect the operator, measuring devices and control equipment from hazards of high voltage. Their use results in safety, accuracy, and convenience.

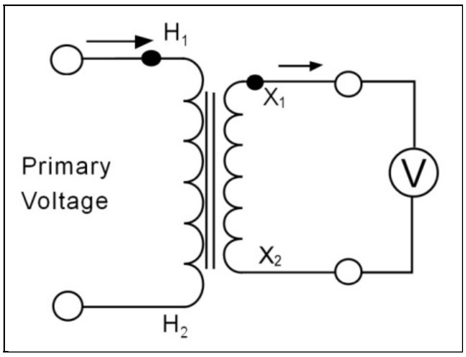


Fig. 1.4-1 Voltage Transformer

Primary winding of VT is connected in parallel to the terminals of the circuit where voltage is to be measured, as shown in Fig. 1.4-2. The secondary winding supplies a voltage proportional to the primary voltage, (normally 100V, 110V, 115V, or 120V secondary).

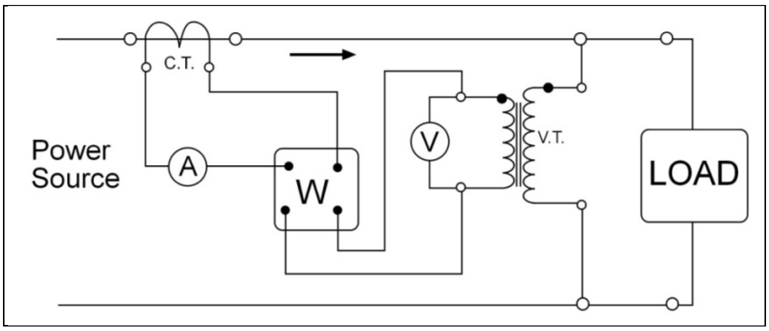


Fig. 1.4-2 Elementary Connections of Instrument Transformers

VOLTAGE TRANSFORMER CONSTRUCTION

TYPES OF VOLTAGE TRANSFORMERS

1- Inductive voltage transformer
2- Capacitor voltage transformer
3- Cascade voltage transformer

The construction of a voltage transformer differs from that of a power transformer. It steps down the voltage to feed measuring or protective equipment. It decreases the voltage by using voltage divider on series capacitors group. The rated output is in the range of a few hundred VA and therefore the heating effect normally has no problem. The size of a PT is largely determined by the system voltage, the insulation of the primary winding often exceeding in volume of the winding itself.

A PT should be insulated to withstand over-voltages, including impulse voltages of a level equal to the withstand value of the switchgear and the high voltage system. To achieve this in a compact design, the voltage must be distributed uniformly across the winding, which requires uniform distribution of the winding capacitance or the application of electrostatic shields. Voltage transformers are commonly used in association with switchgear and the physical design must be compact to be easily adapted for mounting onto or in conjunction with the switchgear used. Three-phase units are common up to 33kV but for higher voltage, single-phase units are more suitable. Voltage transformers for medium voltage circuits have dry type insulation, but for high and extra high voltage systems, oil immersed units are generally installed. Resin encapsulated designs are in use on systems up to 33kV.

INSULATIONS USED IN VOLTAGE TRANSFORMER

Voltage transformers have many types of constructions according to rated voltage. For the lower voltages not exceeding 3.3kV, dry type transformers with varnish impregnated and taped windings are quite satisfactory in reasonably dry locations. For

high voltage, the immersed core and windings in oil give good primary winding insulation. Another type of insulation used is cast resin for a range of 12kV-36kV. A combination of resin and oil is used for up to 100kV, (Fig. 1.4-3 & Fig. 1.4-4).

Fig. 1.4-3 Modern-Resin Insulated VT

Fig. 1.4-4 Outdoor Bushing Voltage Transformer

The voltage transformer is constructed with primary and secondary windings wound on a high-quality steel core. The winding (turns) ratios are precisely controlled to prevent significant voltage ratio errors to obtain a high degree of accuracy. The accuracy of the transformer is also affected by the losses produced in the magnetic

core. Therefore, voltage transformers are carefully designed and constructed to minimize these errors. The construction of the VT is shown in Fig. 1.4-5.

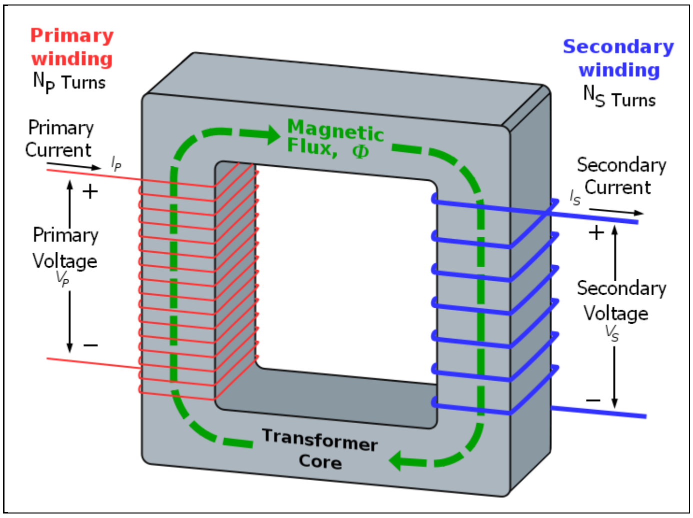


Fig. 1.4-5 Voltage Transformer Construction

Voltage transformers are essentially very similar to distribution transformers. However, because the winding resistance is very low, little heat has to be dissipated from the windings. Therefore, solid insulation without regard to cooling ducts in the winding can be used. Since the transformers are accordingly small and compact, the advantage of combining the lead-in bushings with the transformer is greater than it would be with larger transformers.

FUSING AND PROTECTION OF PT

Simple fuses are used to protect an electromagnetic **PT** from accidental overloads and short circuit across its secondary terminals. For primary winding, the current depends on the primary voltage. The **PT** can be protected by HRC (High-Rupture Capacity) fuses on the primary side for voltages up to 66 kV. At voltages, exceeding 72.5 kV primary fuses are unacceptable and it has become common practice to connect **HV** transformers directly to the line conductor. 145 kV **PTs** could be fitted with Buchholz protection. Capacitor **PTs** are solidly connected to the system with no primary protection.

The secondary side of **PTs** is protected by means of fuses or Miniature Circuit Breakers (MCBs) or a combination of both. There is an advantage in using MCBs as they can give a signal in the event of their tripping out. With fuse protection, only auxiliary relays are provided to indicate a fuse failure. The same disadvantage is inherent in HT fuse protection of **PTs**, (Fig. 1.4-6). The HT fuses also provide a means of isolating the **PTs**, if necessary.

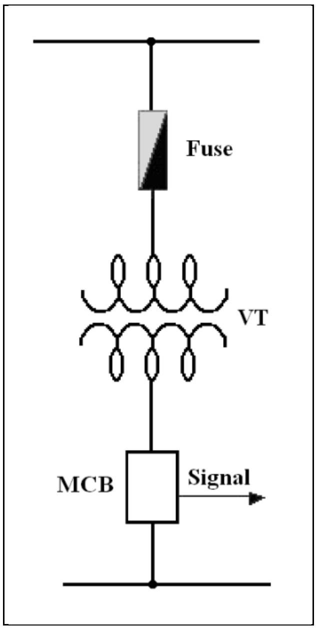


Fig. 1.4-6 PT Fuse Protection

CAPACITOR VOLTAGE TRANSFORMER

As shown in Fig. 1.4-7, a Capacitor Voltage Transformer (CVT), or Capacitance Coupled Voltage Transformer (CCVT) is a transformer used in power systems to step down extra high voltage and provide a low voltage, for measurement or to operate a protective relay. In its most basic form, the device consists of three parts: two capacitors across which the transmission line signal is split, an inductive element to tune the device to the line frequency isolating the PLC, and a transformer to isolate and further step down the voltage for the instrumentation or protective relay.

The device has at least four terminals: a terminal for connection to the high voltage signal, a ground terminal, and two secondary terminals to power up the instrumentation or protective relay. CVTs are typically single-phase devices used for measuring voltages in excess of one hundred kilovolts where the use of conventional voltage transformers would be uneconomical. In practice, capacitor C_1 is often constructed as a stack of smaller capacitors connected in series. This provides a large voltage drop across C_1 and a relatively small voltage drop across C_2. The CVT is also useful in communication systems. CVTs in combination with wave traps are used for filtering high frequency communication signals from power frequency. This forms a carrier communication network throughout the transmission network.

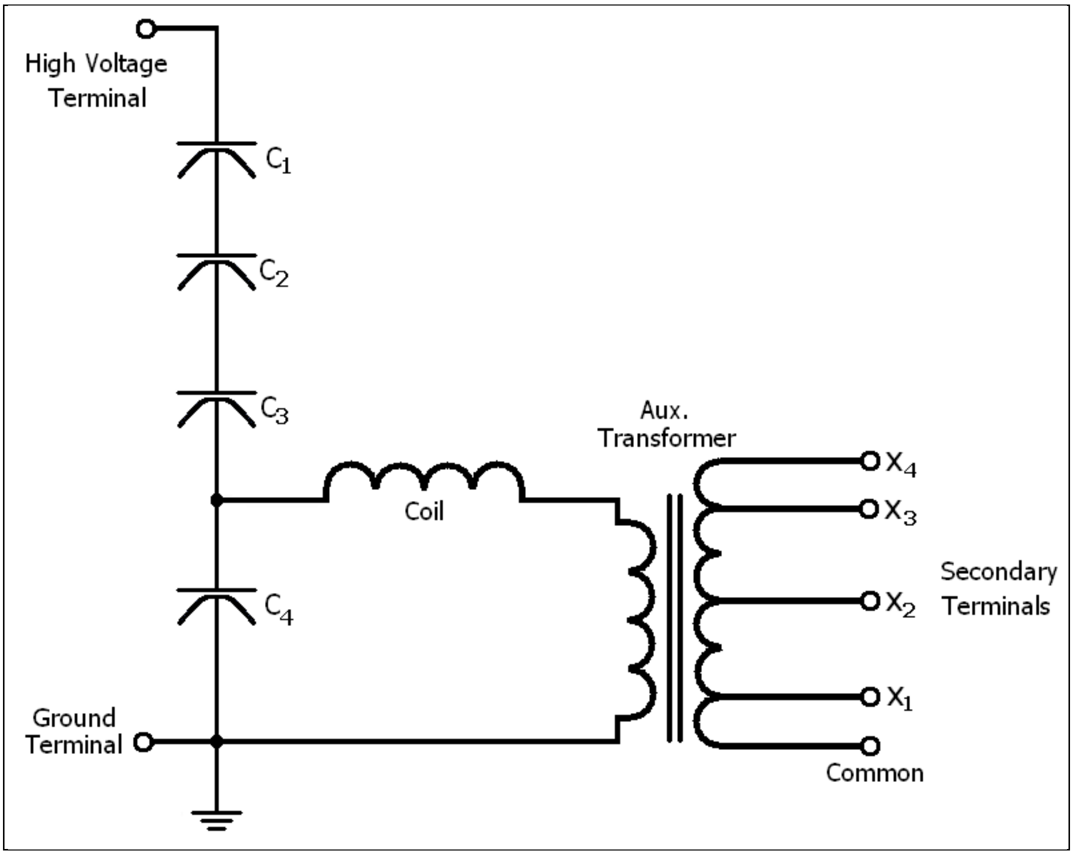


Fig. 1.4-7 Capacitor Voltage Transformer

CASCADED VOLTAGE TRANSFORMER

The capacitor VT was developed because of the high cost of conventional electromagnetic voltage transformers but the frequency and transient responses are less satisfactory than those of the conventional voltage transformers. Another solution to the problem is the cascade VT (Fig. 1.4-8).

The conventional type of VT has a single primary winding, the insulation of which presents a great problem for voltages above about 132kV. The cascade VT avoids these difficulties by breaking down the primary voltage in several distinct and separate stages.

The complete VT is made up of several individual transformers, the primary windings of which are connected in series, as shown. Each magnetic core has primary windings (*P*) on two opposite sides. The secondary winding (*S*) consists

of a single winding on the last stage only. Coupling windings (*C*) connected in pairs between stages, provide low impedance circuits for the transfer of load ampere-turns between stages, and ensure that the power frequency voltage is equally distributed over the several primary windings.

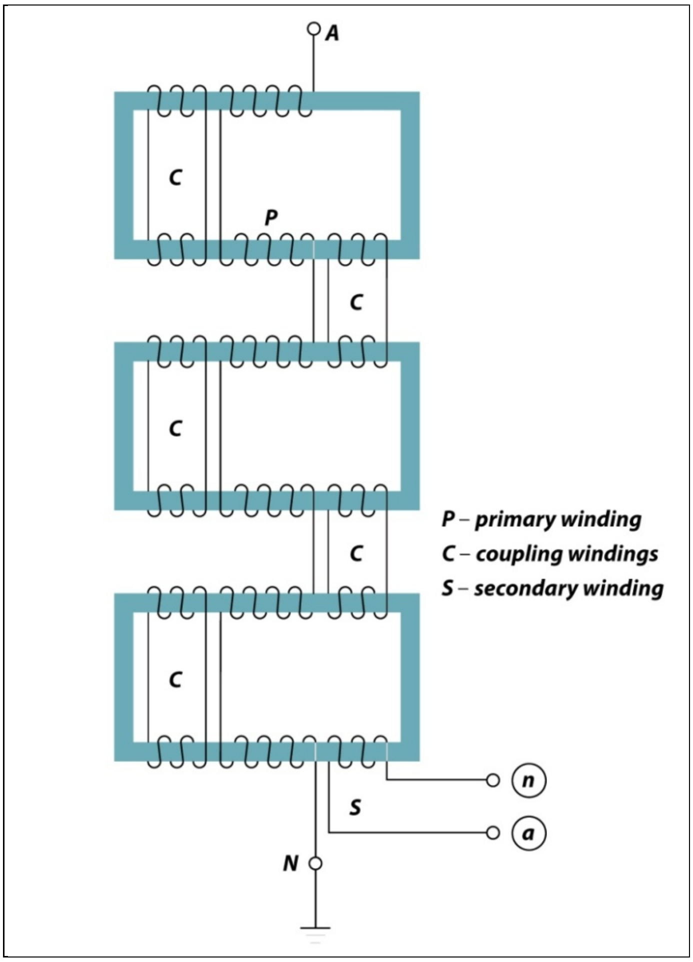


Fig. 1.4-8 Schematic Diagram of Typical Cascade VT

The potentials of the cores and coupling windings are fixed at definite values by connecting them to selected points on the primary windings. The insulation of each winding is sufficient for the voltage developed in that winding, which is a fraction of the total according to the number of stages. The individual transformers are mounted on a structure built of insulating material, which provides the interstage insulation, accumulating to a value able to withstand the full system voltage across the complete height of the stack.

PT CONNECTIONS

The voltage transformer is connected in parallel with the line to step down the Line voltage to 115 or 120 volts for the relay.

NOTE

To keep the voltage for the meters and relays at a safe value, the secondary circuit must be grounded.

TERMINAL MARKING

The terminals of the primary winding of a two-phase voltage transformer are marked with the capital letters U and V and the terminals of the secondary winding with u and v, Fig. 1.4-9a. Single-phase voltage transformers are marked U and X at primary winding and u and x at secondary winding, Fig. 1.4-9b.

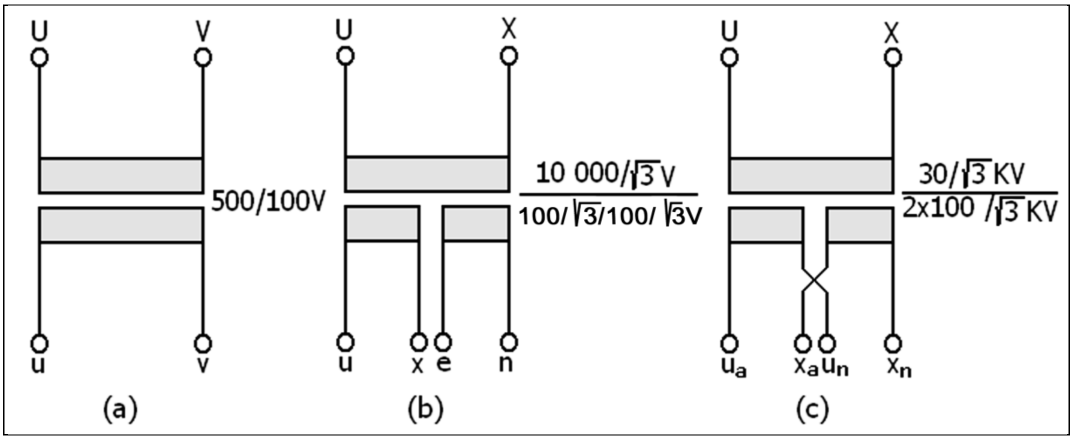


Fig. 1.4-9 VT Terminal Markings

PRIMARY RECONNECTION

For voltage transformers with two or more rated voltages, the voltage selection is done by connecting two or more windings in series or parallel combinations, as required by application. The resulting voltage is indicated by 2 x or 4 x the rated voltage of the selected winding configuration of connection, as shown in Fig. 1.4-10.

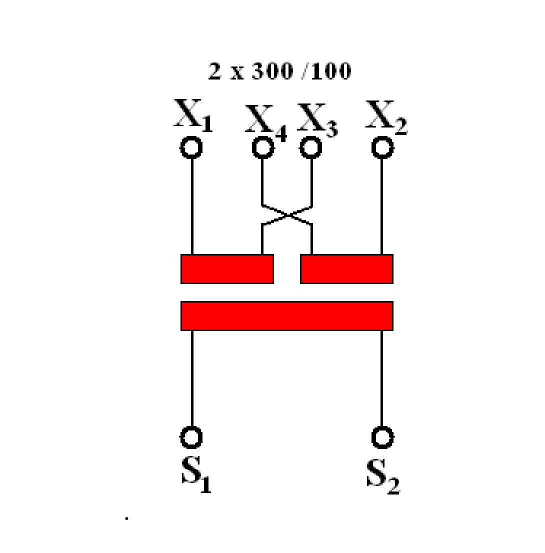


Fig. 1.4-10 Re-Connectable Primary

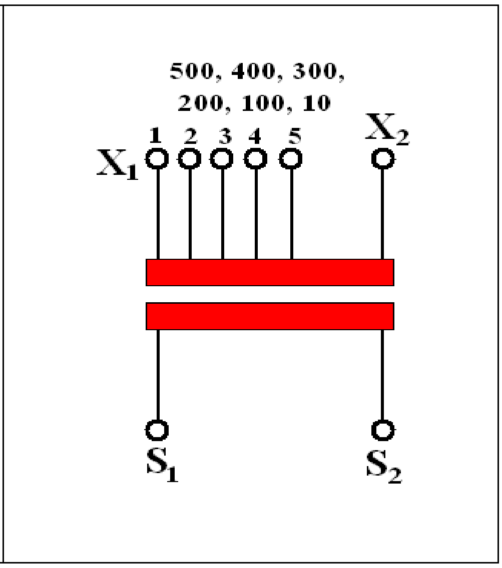


Fig. 1.4-11 Tapped Primary

TAPPED PRIMARY WINDINGS

For tapped primary windings, shown in Fig. 1.4-11, the rated voltages at the individual taps marked by index numbers 1, 2, 3 are separated by semicolons. The entire winding corresponds to the highest value, as shown, for voltage transformers with several independent secondary windings are not intended for connection in series or in parallel, the auxiliary winding is for the monitoring of earth-fault as shown in Fig. 1.4-9.

CONNECTION AND EARTHING

The primary terminal on the earthing side of a single-phase voltage transformer is insulated to withstand a test voltage of 2kV. It can be connected to the housing through an external connection. The point of connection for earthing is marked with the GND symbol ⏚ . Each voltage transformer is provided with a terminal for the connection of protective earthing, but this terminal is not marked ‘protective earth’ as this earth is at the same time the system earth for single-phase voltage transformers. For three-phase connection, the auxiliary windings for the monitoring of earth faults are to be connected in open delta with the free terminal “n” to earth.

VOLTAGE TRANSFORMER BURDEN

The loading of Voltage transformer secondary with measuring or protective devices is called VT burden, as shown in Fig. 1.4-12. Voltage transformer can be loaded with many devices in parallel. As the number of devices in parallel increases, the secondary current (I_S) of the CT also increases, resulting in higher magnetization current (I_M) with proportional losses. Equation (1) describes the current distributed in the VT.

$(I_P /N) = I_S + I_M$ …………………… (1)

Where: **I_P** = Primary current

N = Turns ratio

I_S = Secondary current

I_M = Magnetization current

BURDEN IMPEDANCE (Z_B)

It is the minimum impedance that can be connected on the secondary side without over loading effect on the voltage transformer.

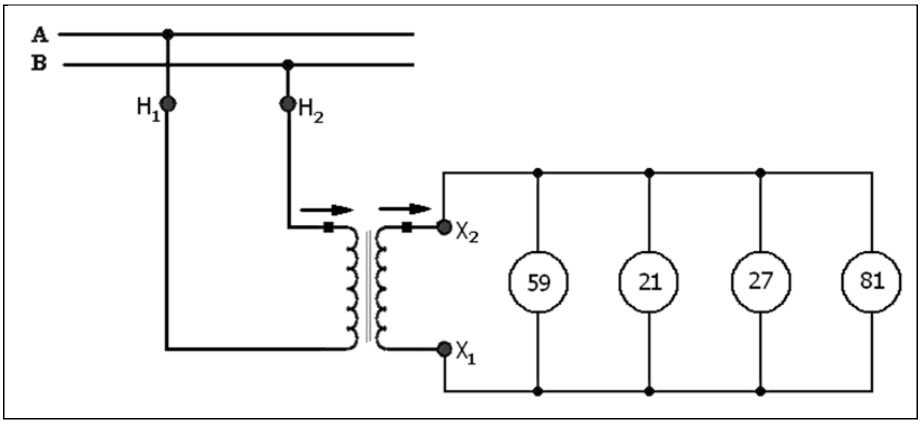


Fig. 1.4-12 VT Burden for Protection

LOAD IMPEDANCE (Z_L)

It is the total actual impedance of the protective or measuring devices that can be connected in parallel with the VT without degradation of the accuracy due to turns ratio error when Z_B must less than Z_L. If Z_L is found to be less than Z_B, it may be dangerous for the VT as it increases the losses due to heating in the winding and core, which may lead to damage for the insulation of the VT and may cause explosion.
For instance, the following devices may be connected in parallel for load impedance calculation from the instruments' specified VA ratings.

MEASURING BURDEN	PROTECTION BURDEN
V: Voltmeter.	59: Over voltage relay.
Var: Reactive power meter.	27: Under voltage relay.
MW: Mega-watt meter.	67: Directional over current relay.
Cos ϕ: Power factor meter.	81: Frequency relay.
MWH: Mega-watt hour meter.	21: Distance relay.

The left side of equation (1) (I_P /N) is a variable value limited with the connected devices; so that any increase in secondary current due to decrease in the load resistance (by adding more devices) results in increase in the magnetization current.
The burden impedance (Z_B) of the VT is calculated according to equation (2).

$$\mathbf{Z_B = (V_S)^2 / VA} \quad \textbf{..............................(2)}$$

Where: **Z_B** = Burden impedance

VA = Voltage transformer capacity (Volt-Ampere rating)

V_S = Secondary voltage

NOTE

It is forbidden to load the VT with a burden less than it has rated one. Otherwise the magnetization current will increase which endanger the voltage transformer.
Because of that the saturation test cannot be performed.

EXAMPLE 1.4-1

A voltage transformer has a secondary voltage of 100V and rated capacity of 10VA. It is required to be connected with three relays, their voltage coils impedances are 4kΩ, 5kΩ, and 6kΩ. Calculate the burden impedance for the VT, and show whither the VT can operate safely with these relays or not.

SOLUTION

Burden impedance of the VT, $Z_B = (V_S)^2$ / VA= $(100)^2$ / 10= **1KΩ**
The total load impedance of the VT, $1/Z_L = 1/4 + 1/5 + 1/6$; Z_L = **1.6KΩ**
It shows that burden impedance (Z_B) is less than load impedance (Z_L). Therefore, the VT will be practically safe to operate.

VOLTAGE TRANSFORMER TESTING

A voltage transformer is tested for three basic characteristics:

- **Insulation resistance Test**
- **Ratio Test**
- **Polarity Test**

INSULATION RESISTANCE TEST

The insulation resistance test detects any short circuits in the insulated winding-to-winding and winding-to-ground. A weak spot in the insulation could cause the instrument transformer to fail in service. For **PTs**, a 500-volt DC Mega-Ohm-meter is generally used. The general requirement is a minimum reading of 1 Mega-Ohm per 1,000 rated volts. A conventional recommended practice requires a minimum of 0.5 MΩ for 120 to 250 secondary volt **PTs.** A minimum value of 1-Mega-Ohm is recommended for transformers rated at 250 to 1,000 volts.

TURNS RATIO TEST

It is important that the turns ratio of a **PT** be accurate so that the secondary can supply a correct proportional voltage to the instruments connected in parallel. The turns ratio test checks for shorted turns of the windings and proper markings of the nameplate voltage and polarity, respectively, for instrument transformers. In the turns ratio test the turns ratio of a transformer is equal to the voltage ratio at no load and can be calculated as follows:

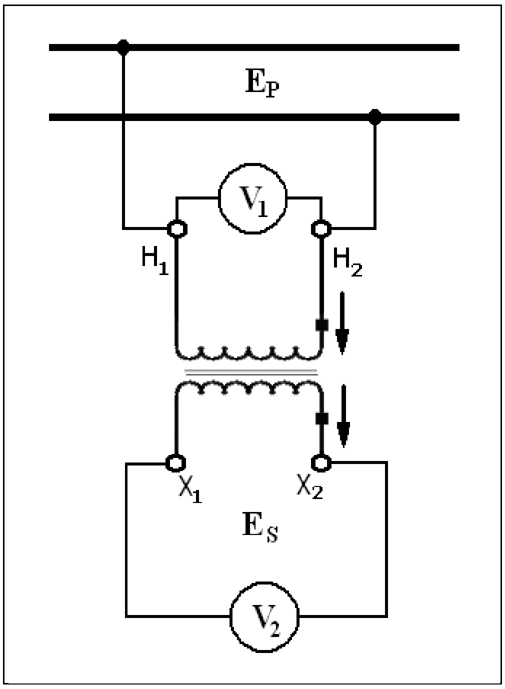


Fig. 1.4-13 Voltage Transformer Ratio Test

$\mathbf{N_P / N_S = V_P / V_S}$

Where: $\mathbf{E_P}$ = Primary voltage

$\mathbf{N_P}$ = Primary turns

$\mathbf{E_S}$ = Secondary voltage

$\mathbf{N_S}$ = Secondary turns

Always test a **VT** by applying a test voltage on the high voltage side and measuring the low-voltage side, (Fig. 1.4-13).

PRECAUTION

On a 2,400 volt to 120 volt PT, injecting the secondary with 120 volts means that the open-circuit primary would be energized with 2,400 volts, stepping up the test voltage, a serious injury or possibly death may result, if contacted, while making connections not being careful, as instructed.

EXAMPLE 1.4-2

Given a VT for test, having a turns ratio of 2400/120 and has 120 volts AC applied to the primary. Determine the resulting voltage on the secondary.

SOLUTION

To determine the voltage ratio, divide the rated primary voltage by the rated secondary voltage, as measured.

2400/120 = 20/1 $V_P / V_S = 20/1$

$V_S = 120 \text{ x } (1/ 20) = 6$ volts

POLARITY TEST

Polarity is important to any directional device. When polarity of the VT is incorrect, false tripping or improper operation of electronic equipment and protective relays may result. Referring to Fig. 1.4-14, at the instant that terminal H_1 is positive, terminal X_1 is also positive.

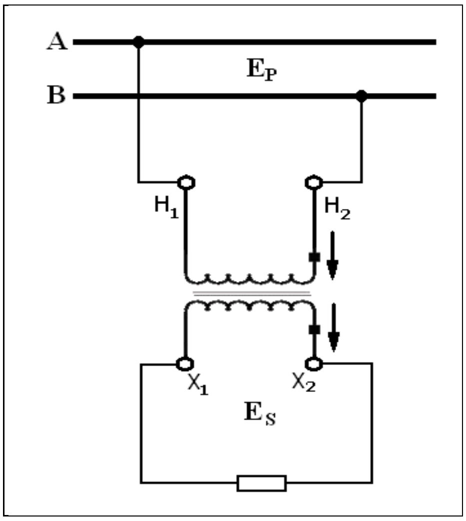


Fig. 1.4-14 Voltage Transformer Polarity

When a voltage transformer's polarity marking is not known, the easiest method of determining polarity is to follow the ANSI procedure (Fig. 1.4-15). Briefly stated, the procedure is as follows:

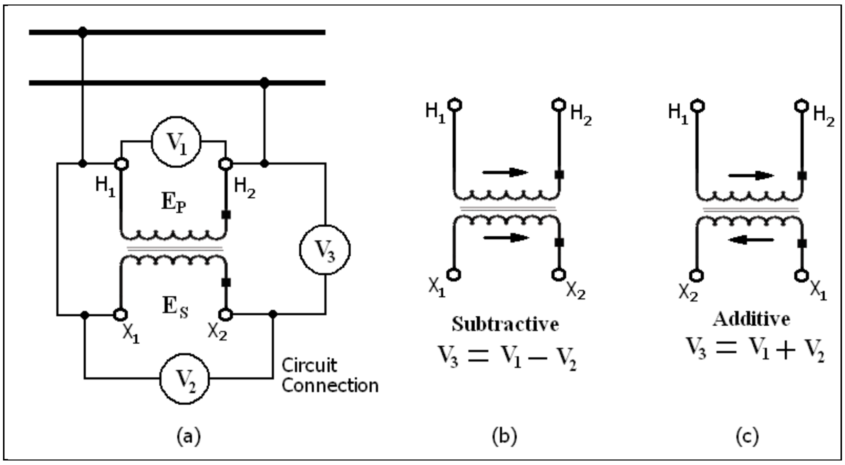


Fig. 1.4-15 Polarity Test

1. Facing the primary high-voltage winding, the H_1 terminal is to the right.
2. Ensure that H_1 has been established.
3. Connect H_1 directly to the adjacent side of the low-voltage terminal **(X_1)**.
4. Install a voltmeter from the opposite low-voltage terminal **(X_2)** to the other high voltage terminal **(H_2)**, Fig. 1.4-15(a).
5. Energize the transformers primary with a suitable source applied between primary terminals H_1 and H_2.

If the voltmeter indicates a voltage **(V_3)** that is higher than the applied voltage **(V_1)**, then the transformer is additive and should be marked, as in Fig. 1.4-15(c). If the voltmeter **(V_3)** indicates a lower voltage than the applied voltage **(V_1)**, then the transformer is subtractive and should be marked, as in Fig. 1.4-15(b). Other test methods can be used to determine polarity, as illustrated in Fig. 1.4-16. The voltage transformer polarity can be checked with the test described for the main current transformer.

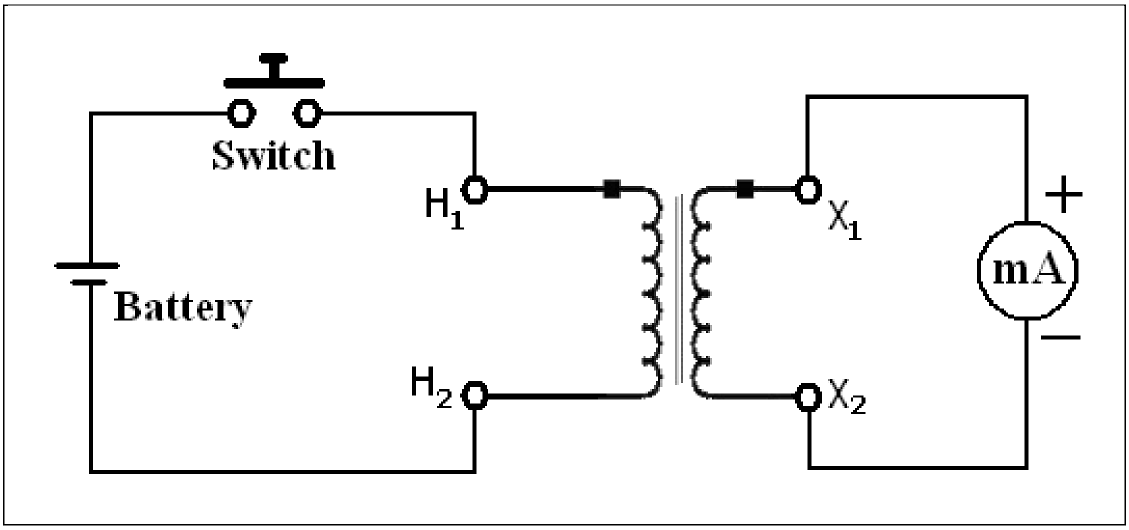


Fig. 1.4-16 PT Polarity Test by DC Supply

Care must be taken to connect the battery supply to the primary winding with the polarity of the ammeter connected to the secondary winding, as shown.

PRECAUTIONS

Extreme caution must be exercised when connecting PTs to ensure that there are no short-circuits on the secondary windings of the PTs. A short-circuit on a PT secondary winding between the MCB or Fuse and PT will result in a break-down of the PT and a possible flash-over internally between the HT primary and LT secondary windings. This may cause an explosion and/or fire and possible damage to adjacent equipment. Where interconnections between the PTs are made in a marshalling kiosk, extreme care should be taken to avoid short-circuiting the PTs or inadvertently interconnecting PT and CT secondary. The circuits connected to the secondary windings should also be tested for short-circuits or low impedance. Under normal circumstances, the secondary circuits should have relatively high impedance. PTs with double-wound secondary are usually delivered with one terminal of each secondary connected to earth at the terminal box. For the ordinary star connected PT, this is normal. However, for the open-delta connection, this earth connection must be removed from the secondary of two phases. Otherwise, when the interconnections are made for the open-

delta connection, a short-circuit will exist, resulting in damage to the PT. Moreover, PTs should not be loaded above their rated burden.

NOTE

Each secondary winding of a PT should be earthed at one terminal and the metal case of the PT should also be earthed. The only exception to this rule is in the case of open-delta connected secondary.

VOLTAGE TRANSFORMER NAMEPLATE

Each VT is provided with nameplate containing all necessary information and technical data (Fig. 1.4-17), as specified by the Manufacturer.

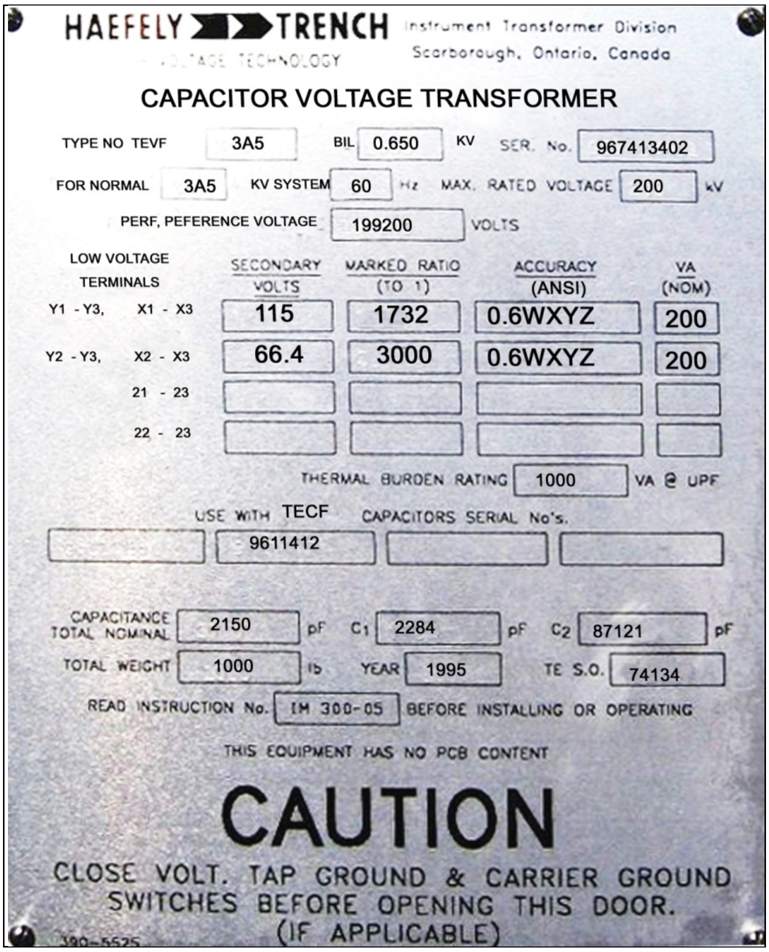


Fig. 1.4-17 Voltage Transformer Nameplate

SUMMARY

- Voltage transformer is used to decrease voltage from kilo volts to small value of volts.
- The burden of the VT is calculated for all device impedances connected in parallel with the secondary.
- The insulation test using a megger tests the VT at a voltage suitable for voltage transformer.
- Polarity test of VT is done by small AC voltage applied on the primary side.
- Turns ratio test is accomplished by applying voltage to primary and monitoring secondary voltage on a voltmeter.
- The two applications of VTs are Protection and Metering.

- The cascaded **VT** having the primary windings in several sections connected in series, steps down the high voltage in stages and makes the PT size smaller having lower oil content, resulting in more economical than conventional **VT**s.
- The auxiliary secondary winding of voltage transformer, marked **"e"** and **"n"** is used for monitoring earth-faults.
- The general requirement of insulation is a minimum reading of 1 MΩ per 1,000 rated volts.
- A recommended practice requires a minimum of 0.5 Mega-Ohm for 100 to 120 secondary volt **VTs.**.
- The turns ratio test checks for shorted turns of the windings.
- In the turns ratio test, the turns ratio of a transformer is at no load.
- DC polarity test of PT requires connecting the battery supply to the primary winding with the polarity ammeter connected to the secondary winding.

FORMULAE

$Z_B = (V_S)^2 / VA$

Where: Z_B = Burden impedance
VA = Voltage transformer capacity
V_S = Secondary voltage of the VT

$N_P/N_S = V_P / V_S$

Where: $\mathbf{V_P}$ = Primary voltage
$\mathbf{N_P}$ = Primary turns
$\mathbf{V_S}$ = Secondary voltage
$\mathbf{N_S}$ = Secondary turns

GLOSSARY

ANSI:	American National Standards Institute.
MCB:	Miniature Circuit Breaker
HRC:	High Rupture Capacity
VT burden:	The total device impedances connected in parallel
Capacitor VT:	Uses series capacitors to divide the primary voltage

REVIEW EXERCISE

I)-Select the correct answers:

1. The burden devices are connected ______ with the secondary of the voltage transformer :
   a) In series. b) In parallel.

2. The load impedance of the voltage transformer must be:
   a) Equal to burden impedance. b) Greater than burden impedance.
   c) Never mind. d) Less than burden impedance.

3. The insulation test is applied by:
   a) Using megger. b) Using primary injection device.
   c) DC supply. d) Normal voltage source.

4. Polarity test of the VT is not necessary for measuring:
   a) Active power. b) Voltage.

5. Polarity test is necessary for VT that operates:
   a) Overvoltage relay. b) Under voltage relay.
   c) Distance relay. d) Earth fault relay.

6. Polarity test of the VT is necessary when using with:
   a) MVar meter. b) KWH meter.
   c) Frequency meter d) Both a & b

II) Answer the following questions:

1. Draw a simple diagram of a VT connected to a power line.

2. Find the primary voltage of a VT with nameplate rating of 132kV/√3/110/√3, if the secondary winding connected to a voltmeter indicates 108V.

3. Explain why there is no saturation test for the VT.

4. Explain, with a drawing what polarity means.

III) Answer the following with True or False:

1.	Turns ratio test is performed by DC source.		
2.	Load devices of voltage transformer are connected in parallel.		
3.	The energized VT secondary can be short circuited without loads.		
4.	VT primary winding is connected in parallel with the system.		
5.	Saturation test for the VT is performed by primary injection test set.		
6.	Capacitor voltage transformer has divider of series capacitors.		

IV) A voltage transformer has a secondary voltage of 120V and rated capacity of 12VA. It is required to be connected with three relays having voltage coil impedances of 4kΩ, 6kΩ, & 8kΩ. Calculate the burden impedance for the VT, and show if this VT can operate safely with these relays or not.

TASK 1.4-1

INSPECTION OF VT & READING NAMEPLATE

OBJECTIVE

Upon completion of this task, the participants will be able to:

1. Inspect voltage transformer and read nameplates.

TOOLS, EQUIPMENT AND MATERIALS

1 – Any type of voltage transformer.

PROCEDURE

1. Receive the following from the instructor:
   a. Different types of **VTs**.
   b. Safety instructions

2. Visually, inspect each type of given **VTs**.

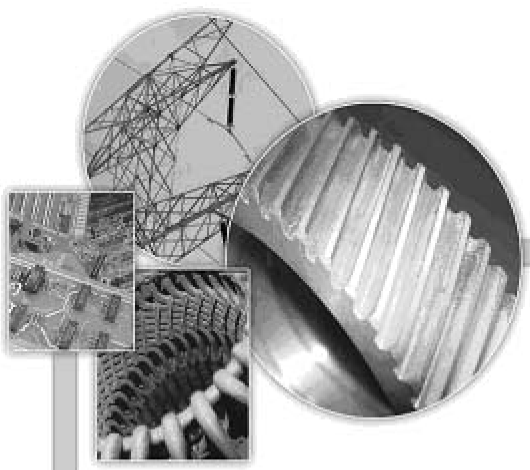
3. Determine the secondary and primary terminals.

4. Read the nameplate for each **VT.**

5. Determine the accuracy class, nominal ratio, insulation, and VA of **VT.**

6. Ask the instructor to check the work.

7. Clean up after finishing the task.



UNIT 2

CIRCUIT BREAKER & CONTROL CIRCUITS

UNIT-2
CIRCUIT BREAKER & CONTROL CIRCUITS

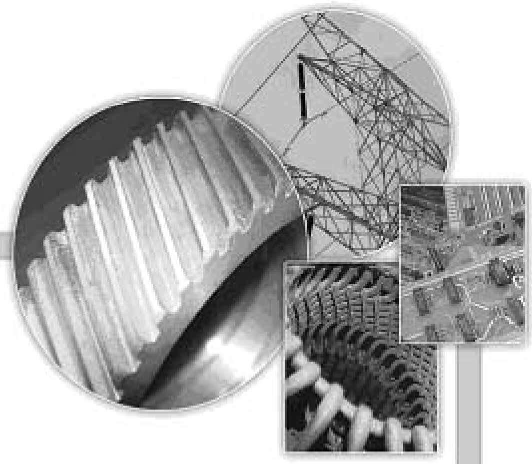
OVERVIEW

In this unit, the trainees learn the different types of electrical drawings to understand the operation of the power system. Each type of electrical diagrams uses standard symbols and abbreviations to simplify for better understanding. In addition, different types of circuit breakers with their operating mechanisms and their associated control circuits for closing and tripping operations are discussed.

OBJECTIVES

Upon completion of this unit, the trainees will be able to:

- Identify the different types of electrical drawings.
- Demonstrate the main types of circuit breaker.
- Illustrate the circuit breaker control circuits.
- Demonstrate and identify the interlocks of CB closing and tripping operation.



LESSON 2.1

TYPES OF ELECTRICAL DIAGRAMS

LESSON 2.1
TYPES OF ELECTRICAL DIAGRAMS

OVERVIEW

In this lesson, the trainee learns how to read different types of electrical drawings for the purpose of troubleshooting, installation, and maintenance. The lesson describes the contents of a drawing such as equipment, symbols, abbreviations, device function numbers, and modes of operation. There are many types of electrical diagrams. Each type provides different information. The types of electrical diagrams are block diagrams, single line diagrams, layout diagrams, schematic diagrams, and wiring diagrams.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Classify types of electrical diagrams.
- Describe block diagrams.
- Identify single line diagrams.
- Demonstrate schematic diagrams.
- Illustrate wiring diagrams.
- Identify layout diagrams.

INTRODUCTION

Electrical diagrams are the most used document used among technicians, engineers, and supervisors to understand the behavior of electrical power system. It is powerful tool to help in troubleshooting and to understand the essential operation of the power system.

BLOCK DIAGRAMS

Block diagram is used to describe relationship between some processes without details to produce effective output. The diagram may have some blocks, each block having at least one input and one output.

It provides a basic overview for an electrical system and shows how the parts of the electrical system are connected to each other. It is usually simple and does not include much information about its operation.

An example to describe how the electric power is produced from power generator is shown in Fig. 2.1-1.

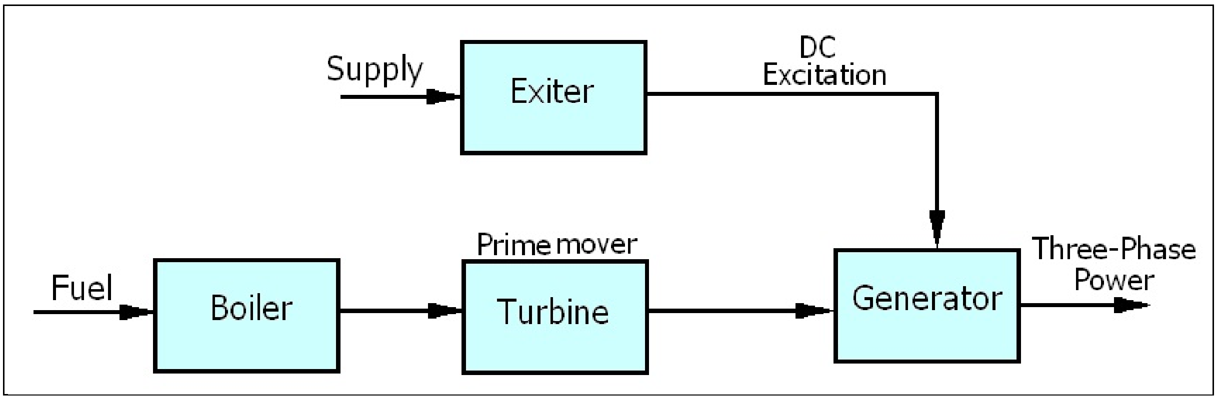


Fig. 2.1-1 Producing Three-Phase Power from Power Generator

An example to describe the static overcurrent relay operation is represented by a block diagram, as shown in Fig. 2.1-2.

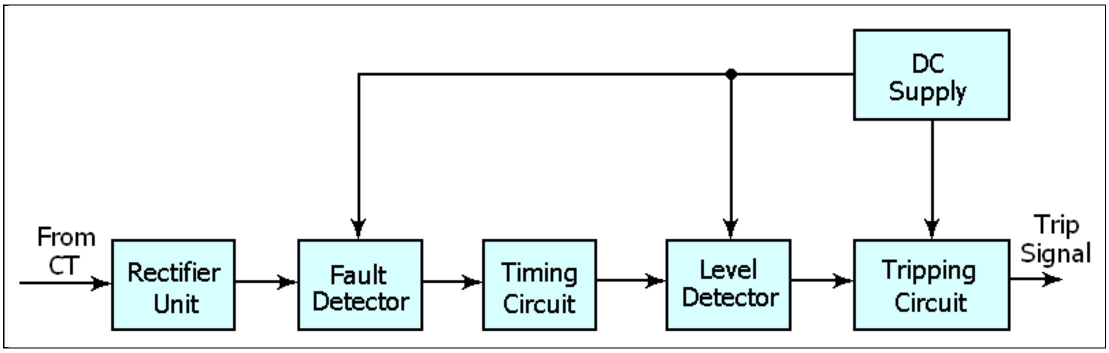


Fig. 2.1-2 Simple Static Overcurrent Relay Circuit

Note that each block represents an electronic circuit that may exist on a separate printed circuit board and has tuning adjustment to operate with the other circuits.

SYMBOLS FOR POWER SYSTEM EQUIPMENT

The elements of power system are represented by standard electrical symbols, as shown in the following figures.

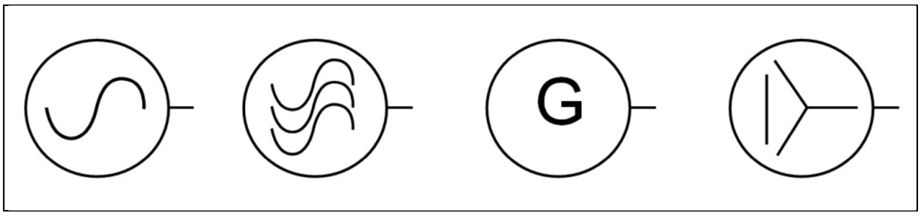


Fig. 2.1-3 Different Symbols for System Generator

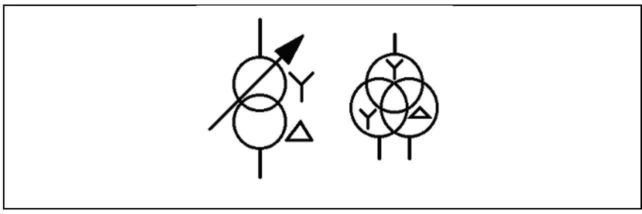


Fig. 2.1-4a Three Phase Transformer

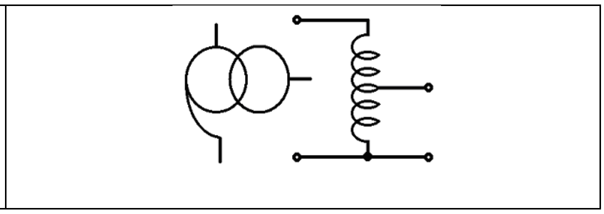


Fig. 2.1-4b Auto Transformer

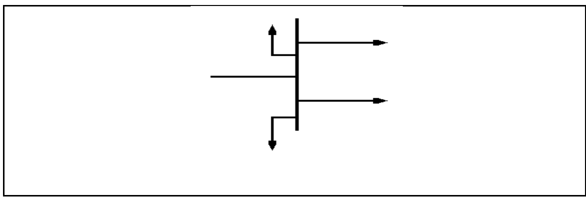


Fig. 2.1-5a Single Bus-bar

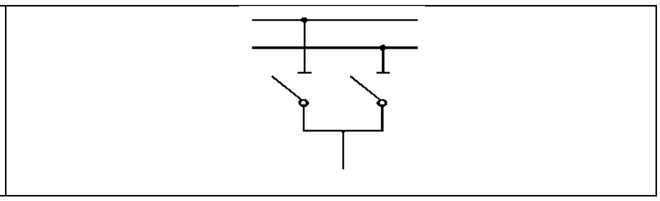


Fig. 2.1-5b Double Bus bar

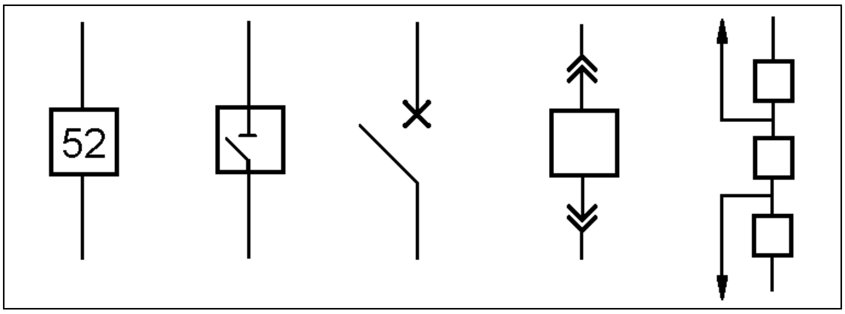


Fig. 2.1-6 Circuit Breaker Symbols

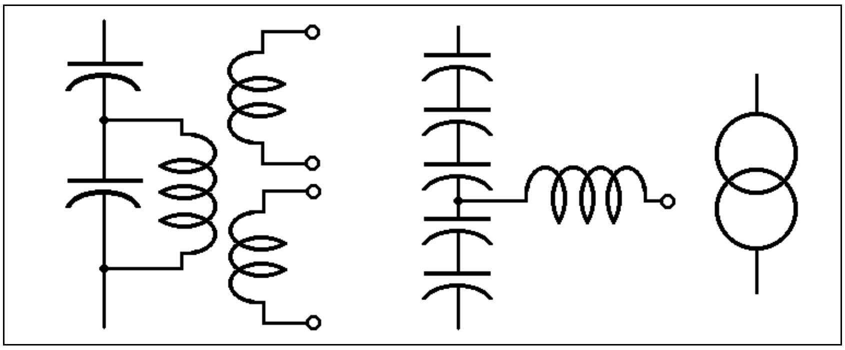


Fig. 2.1-7 Voltage Transformer Symbols

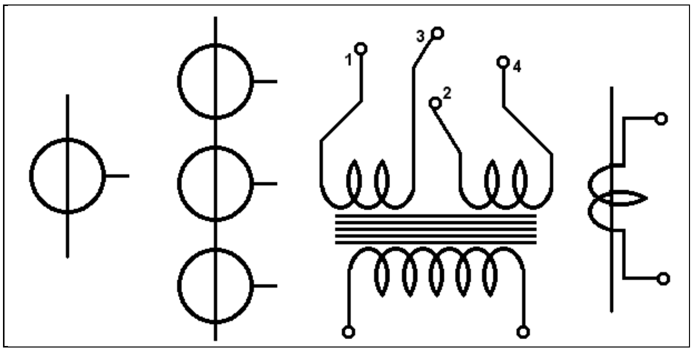


Fig. 2.1-8 Current Transformer Symbols

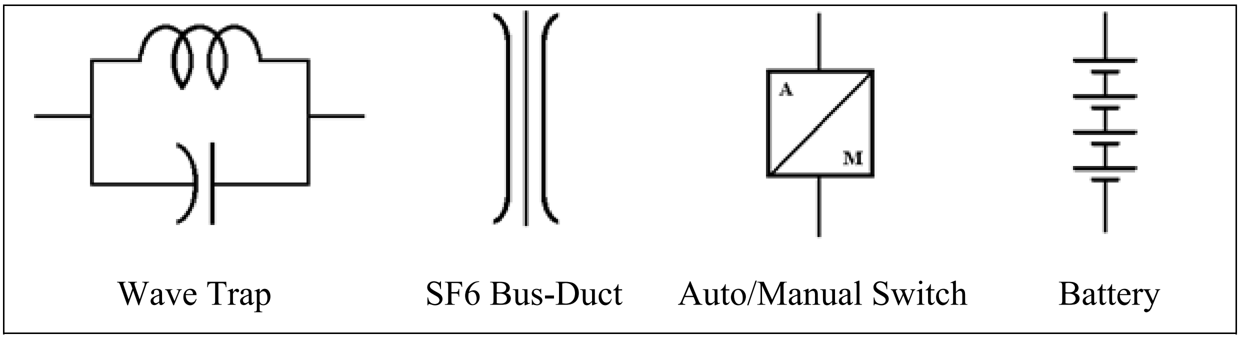


Fig. 2.1-9

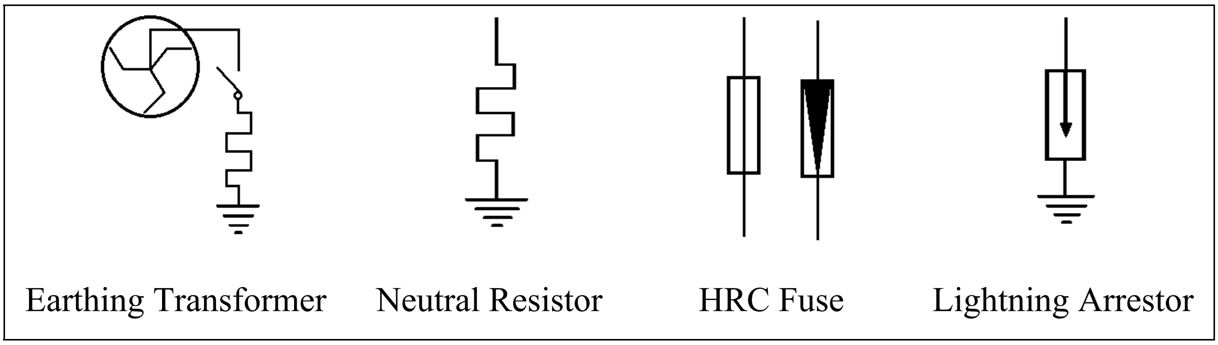


Fig. 2.1-10

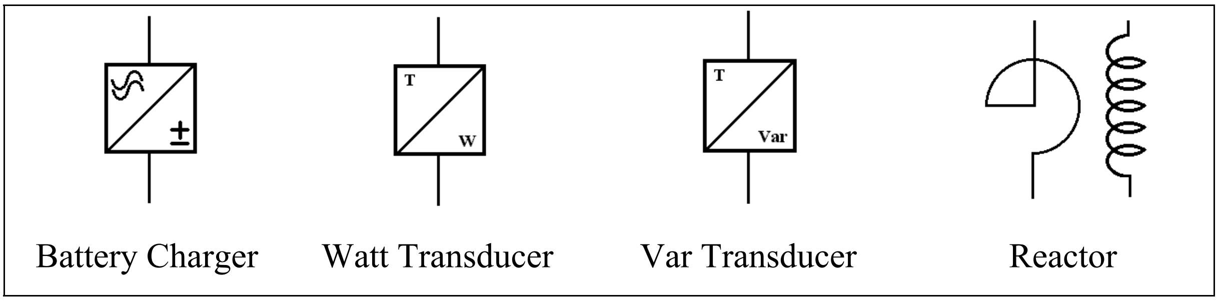


Fig. 2.1-11

Some power equipment drawings contain symbols with different electrical standards depending on the manufacturer, European or North American such as those in different single line diagrams.

SYMBOLS FOR CONTROL DEVICES

The American Standard Device Function Numbers identifies the general functions of many electrical devices in terms of number designations, as shown in Table 2.1-1.

No.	Description	No.	Description
1	Master element	2	Time-delay starting or closing relay
3	Checking or interlocking relay	4	Master contactor
5	Stopping device	6	Starting circuit breaker
7	Rate-of-rise relay	8	Control power disconnecting device
9	Reversing device	10	Unit sequence switch
11	Multifunction device	12	Over speed device
13	Synchronous-speed device	14	Under speed device

15	Speed or frequency matching device	16	Reserved for future application
17	Shunting or discharge switch	18	Accelerating or decelerating device
19	Starting-to-running transition contactor	20	Electrically operated valve
21	Distance relay	22	Equalizer circuit breaker
23	Temperature control device	24	Volts per hertz relay
25	Synchronizing check device	26	Apparatus thermal device
27	Under voltage relay	28	Flame detector
29	Isolating contactor	30	Anunciator relay
31	Separate excitation device	32	Directional power relay
33	Position switch	34	Master sequence device
35	Brush-operating or slip-ring short-circuiting device	36	Polarity or polarizing voltage device
37	Undercurrent or under power relay	38	Bearing protective device
39	Mechanical condition monitor	40	Field relay
41	Field circuit breaker	42	Running circuit breaker
43	Manual transfer or selector device	44	Unit sequence starting relay
45	Atmospheric condition monitor	46	Reverse-phase or phase-balance current relay
47	Phase-sequence or phase-balance voltage relay	48	Incomplete sequence relay
49	Thermal relay	50	Instantaneous over current relay
51	AC time over current relay	52	AC circuit breaker
53	Exciter or dc generator relay	54	Turning gear engaging device
55	Power factor relay	56	Field application relay
57	Short-circuiting or grounding device	58	Rectification failure relay
59	Over voltage relay	60	Voltage or current balance relay
61	Density switch or sensor	62	Time-delay stopping relay
63	Pressure switch	64	Ground detector relay
65	Governor	66	Notching or jogging device

67	AC directional over current relay	68	Blocking relay
69	Permissive control device	70	Rheostat
71	Level switch	72	DC circuit breaker
73	Load-resistor contactor	74	Alarm relay
75	Position changing mechanism	76	DC over current relay
77	Tele-metering device	78	Phase-angle measuring or out-of-step protective relay
79	AC reclosing relay	80	Flow switch
81	Frequency relay	82	DC load-measuring reclosing relay
83	Automatic selective transfer relay	84	Operating mechanism
85	Carrier or pilot-wire receiver relay	86	Lockout relay
87	Differential protective relay	88	Auxiliary motor or motor generator
89	Line switch	90	Regulating device
91	Voltage directional relay	92	Voltage and power directional relay
93	Field-changing contactor	94	Tripping or trip-free relay

Table 2.1-1 Device Function Numbers

SUFFIX LETTERS (Abbreviations)

Suffix letters are used with device function numbers for various purposes. In order to prevent possible conflict, any suffix letter used singly, or any combination of letters, denotes only one word or meaning particular equipment. Furthermore, the meaning of each single suffix letter, or combination of letters, should be clearly designated in the legend on the drawings of publications applying to the equipment.

NOTE

In the control of a Circuit Breaker with so-called X - Y relay control scheme, the X relay is the device whose main contacts are used to energize the closing coil and the contacts of the Y relay provide the anti-pump feature for the Circuit Breaker.

C	Coil or Condenser or Capacitor
CC	Closing Coil
HC	Holding Coil
IS	Inductive Shunt
L	Lower Operating Coil
M	Motor
S	Solenoid
TC	Trip Coil
U	Upper Operating Coil
V	Valve

All auxiliary contacts and limit switches for such devices and equipment as Circuit Breakers, contactors, valves and rheostats are designated as follows:

a	Auxiliary switch, open when the main device is in the de-energized or non-operated position.
b	Auxiliary switch, closed when the main device is in the de-energized or non-operated position.
aa	Auxiliary switch, open when the operating mechanism of the main device is in the de-energized or non-operated position.
bb	Auxiliary switch, closed when the operating mechanism of the main device is in the de-energized or non-operated position.
LC	Latch-Checking switch, closed when the Circuit Breaker-mechanism linkage is re-latched after an operation of the Circuit Breaker.
LS	Limit Switch
H	Hot or High
HR	Hand Reset
HS	High Speed
IT	Inverse Time
L	Left or Local or Low or Lower or Leading

M	Manual
OFF	Off
ON	On
O	Open
P	Polarizing
R	Right or Raise or Reclosing or Receiving or Remote or Reverse
S	Sending or Swing
T	Test or Trip or Trailing
TDC	Time-Delay Closing
TDO	Time-Delay Opening
U	Up

Abbreviations used in the Standard Diagrams identify components. For example, HC is the standard diagram abbreviation for a 'Holding Coil' and CS is the abbreviation for a Control Switch.

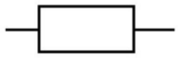
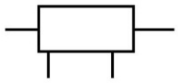
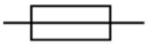
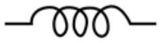
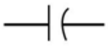
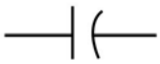
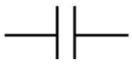
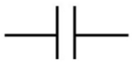
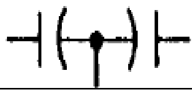
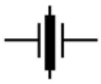
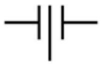
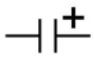
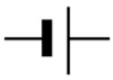
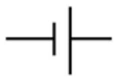
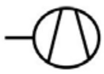
Description	International Symbols	US/ Canadian Symbols	British Symbols	German Symbols
Resistor	= or 	= or 	= or 	
Resistor With Taps	=	=	=	
Winding, Inductor	= or  or 		 or 	
Inductor With Taps				
Capacitor	= or 			
Capacitor With Taps	=			
Polarized Capacitor	=	=		
Battery	=	=		
Ground	=	=	=	
Electrical Driven Fan		—		

Fig. 2.1-12 General Circuit Elements

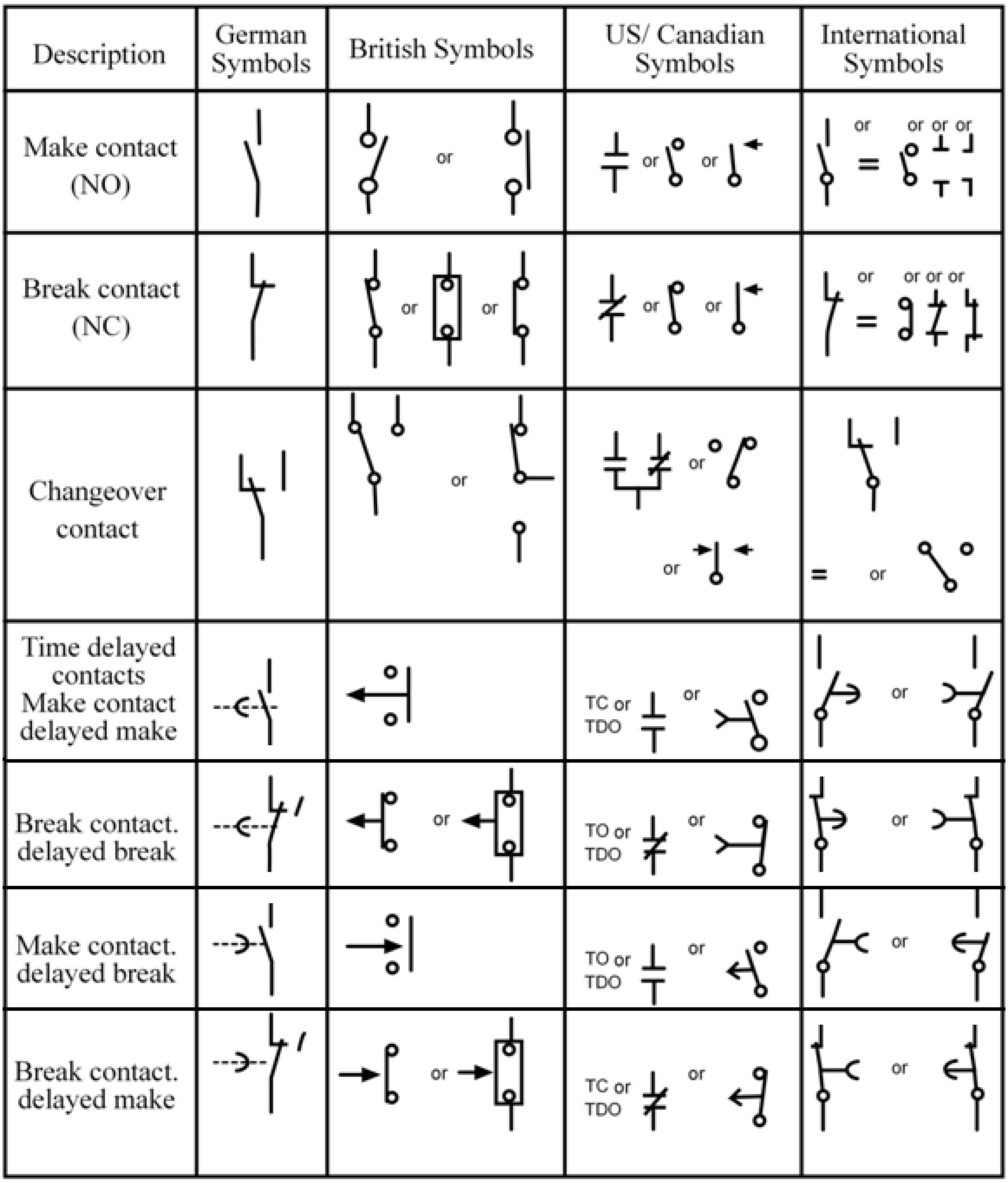


Fig. 2.1-13 General Circuit Elements

Description	German Symbols	British Symbols	US/Canadian Symbols	International Symbols
Single Throw Manually Operated				–
Manual Operated NO Contact				=
Manual Operated NC Contact				=
Foot Operated				
Cam Operated			or	
Flow Operated				=
Temperature Operated				= or
Liquid Level Operated				
Pressure Operated				=

Fig. 2.1-14 Switches and contacts

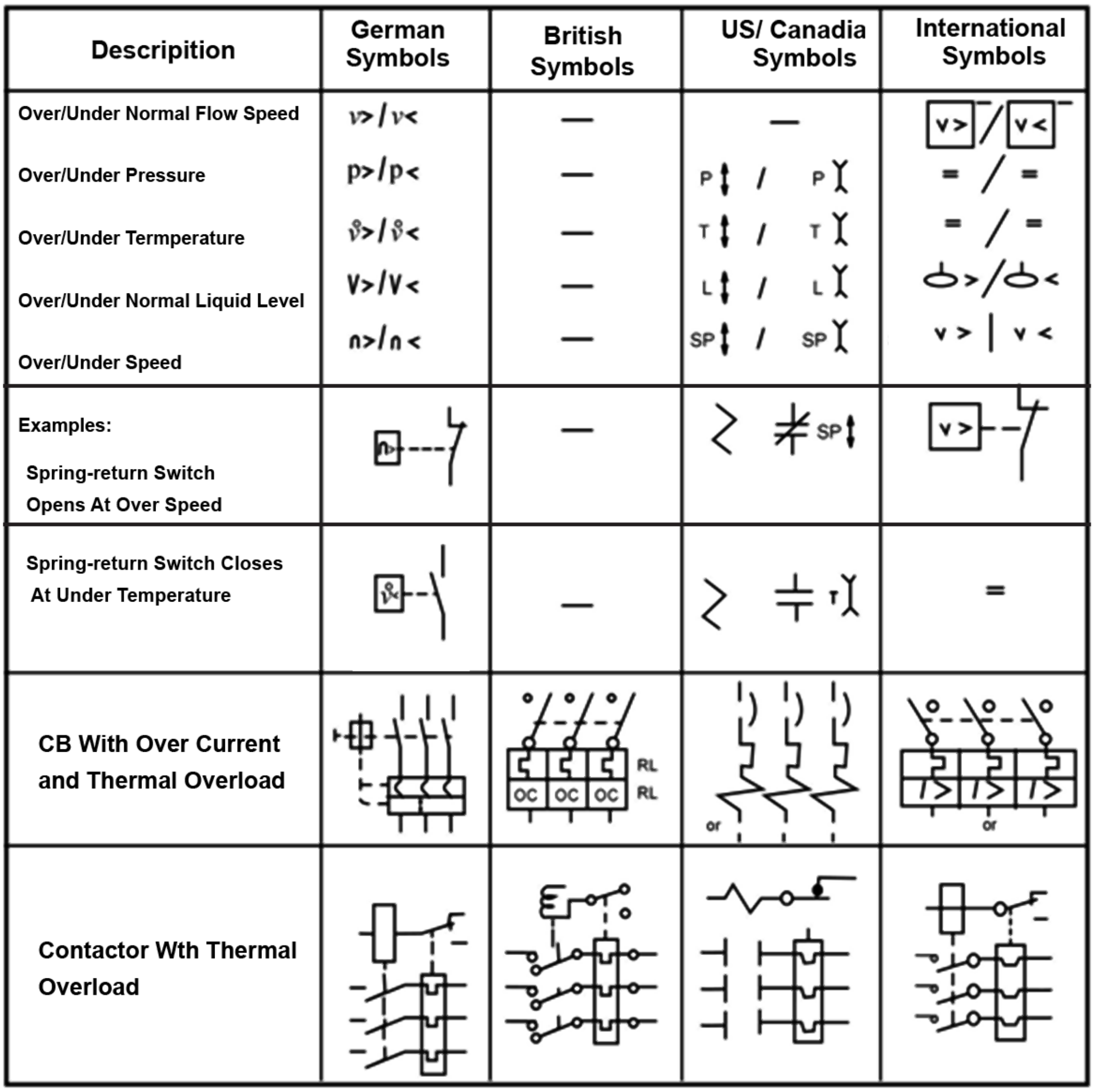


Fig. 2.1-15 Switches and contacts

SINGLE LINE DIAGRAMS

Single line diagrams describe and simplify three-phase power circuits representing with only one line per circuit, instead of drawing the three lines of the three-phase circuit.

They are used to represent arrangement of the main power system equipment such as system generation, power transformer, switchgears, bus bars, cables, and transmission lines. Single line diagrams typically use standard electrical symbols to represent the system equipment as shown in Fig. 2.1-12 & 13.

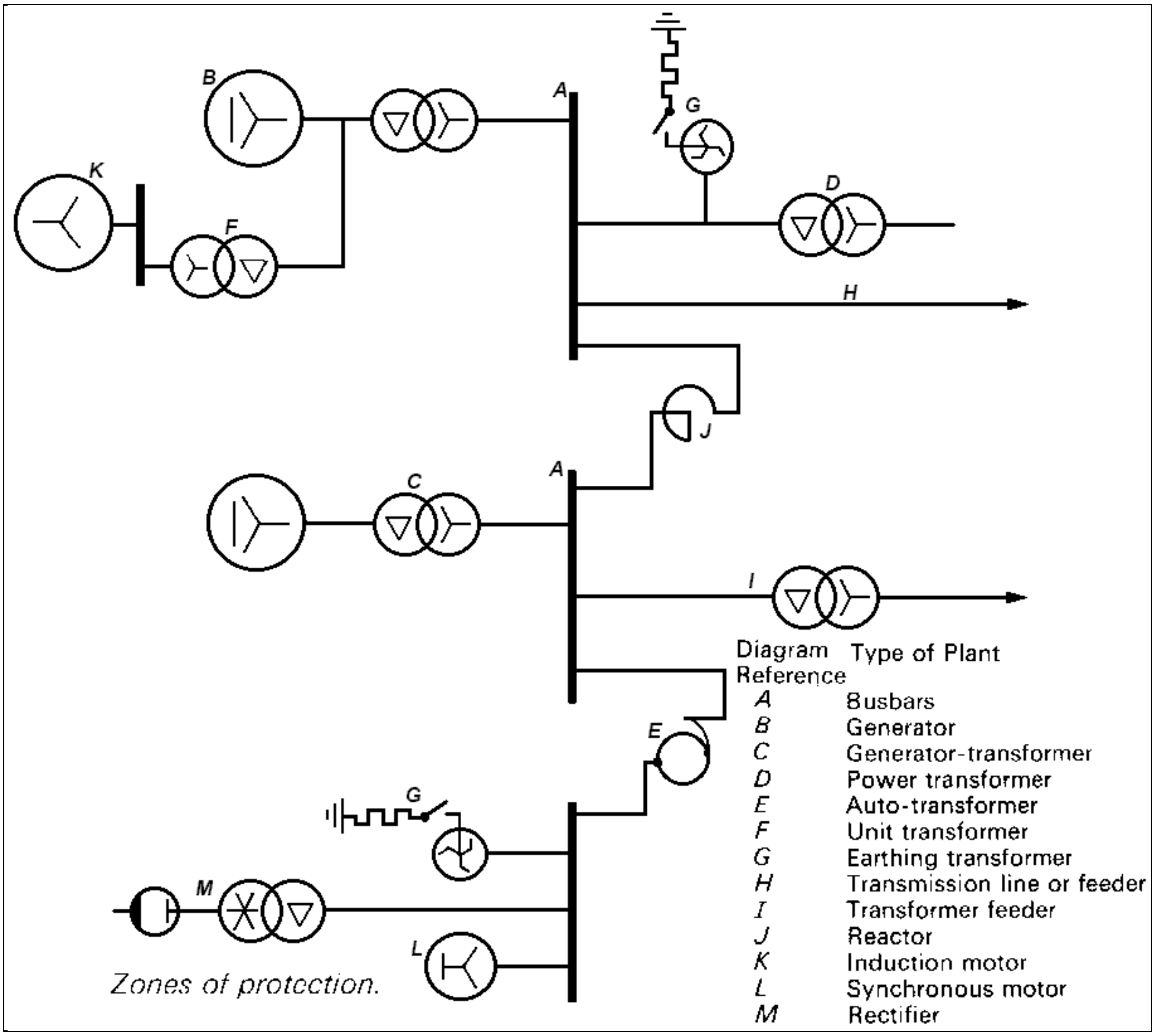


Fig. 2.1-16 Typical Single Line Diagram for Power Station

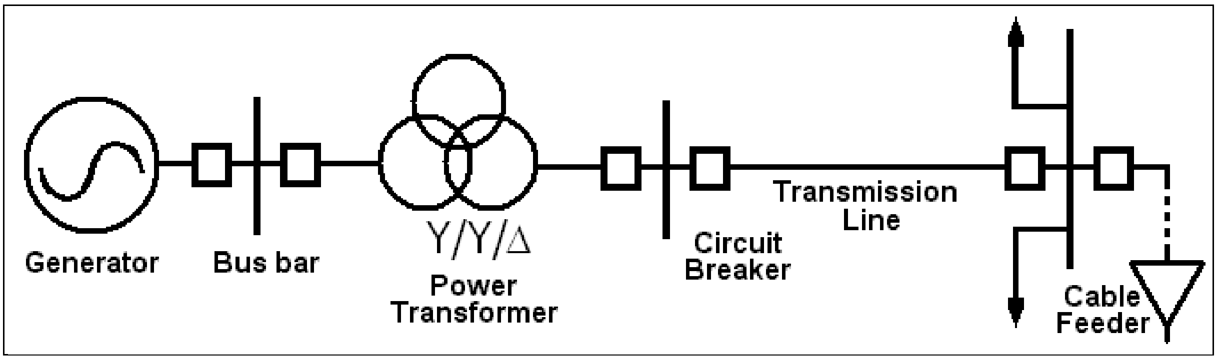


Fig. 2.1-17 Simple Single Line Diagram for Power System Configuration

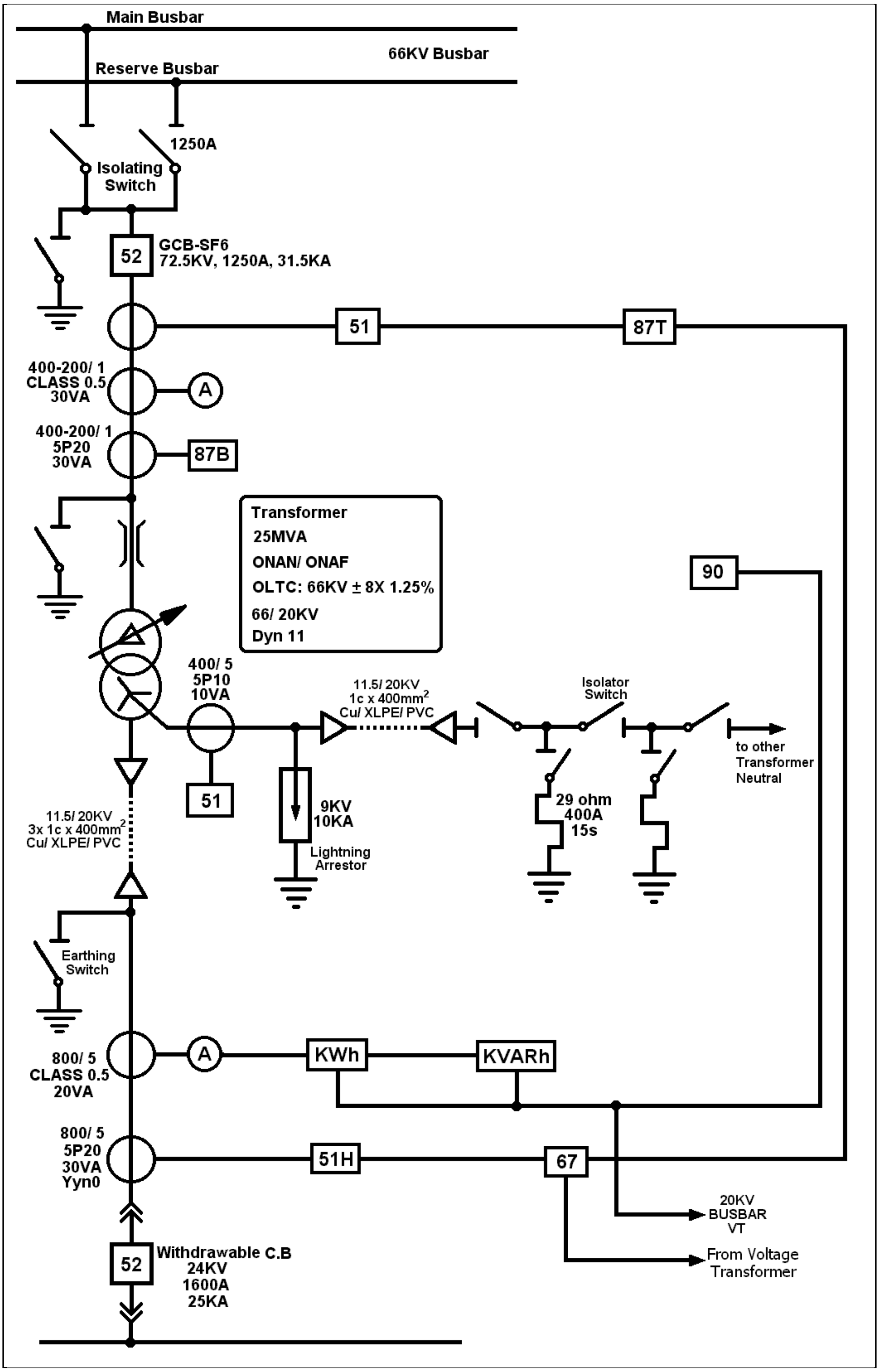


Fig. 2.1-18 Single Line Diagram showing Transformer Protection & Measurement Scheme

SCHEMATIC DIAGRAMS

Schematic diagrams show all of the components in a unit and how they are electrically connected. They show components in their proper electrical positions, but not necessarily in their proper physical locations. Schematic diagrams are read from left to right and from top to bottom. They typically use standard electrical diagram symbols and device function numbers. **The positions of the contacts and switches are shown, as they would be in the de-energized state.**

Note

Refer to appendix for more standard device function numbers.
Fig. 2.1-19 shows an example for schematic diagram of a three-phase AC motor control circuit. As with all motor controller diagrams, the schematic drawing is divided into two circuits, motor power circuit and control circuit .

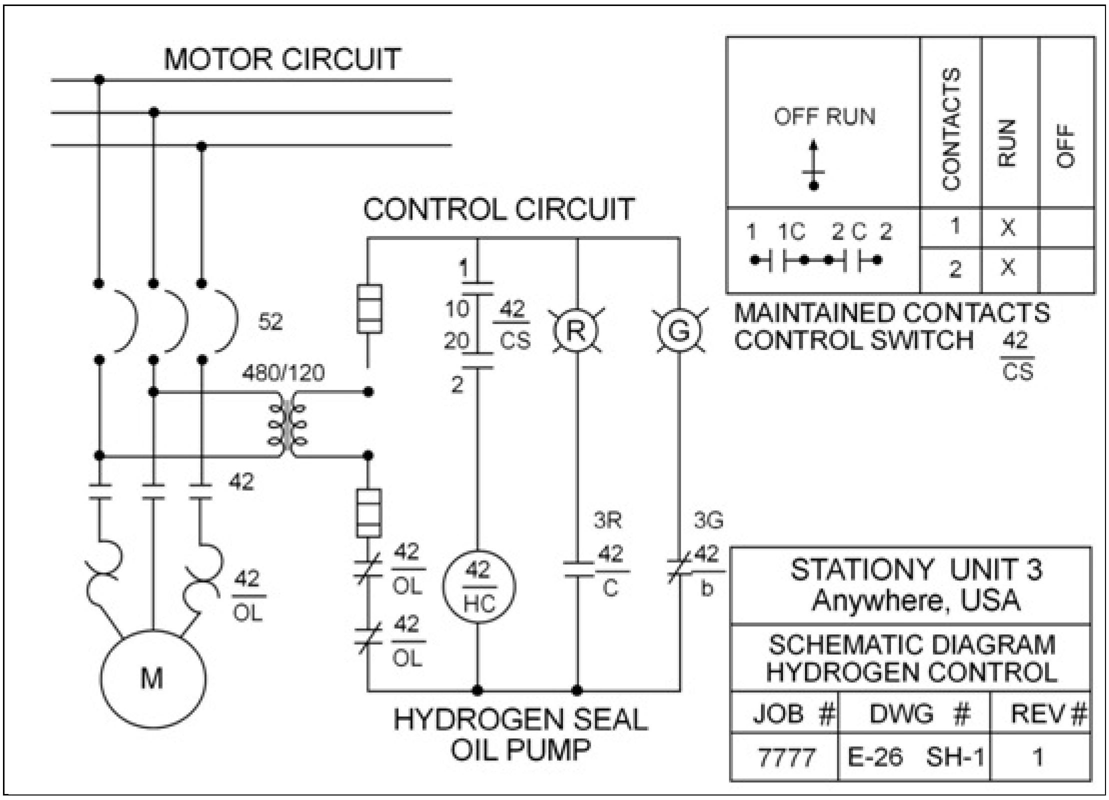


Fig. 2.1-19 Schematic Diagram for Motor Control Circuit

WIRING DIAGRAMS

Wiring diagrams are used to describe installation of electrical circuit, as to how terminals are electrically connected to components with terminal labels bearing numbers. For example, although schematics show all of the components in a unit in their correct electrical positions, they do not usually show the components in their correct physical locations or in their correct physical relationships to each other. In order to locate components physically in a unit, it is usually necessary to use a wiring diagram, as shown in Fig. 2.1-20.

The wiring diagram shows the physical relationship of the individual parts of major components to each other. For example, this diagram shows where the holding coil and its contacts are physically located. A good way of using a wiring diagram is to locate a major component on the diagram, using it as a point of reference and identifying all of the other components in relation to it. As an example, in Fig. 2.1-20, consider the holding coil as the major component as a point of reference. The other components can be physically located above the holding coil, below it, to the right or left of it, behind it or in front of it.

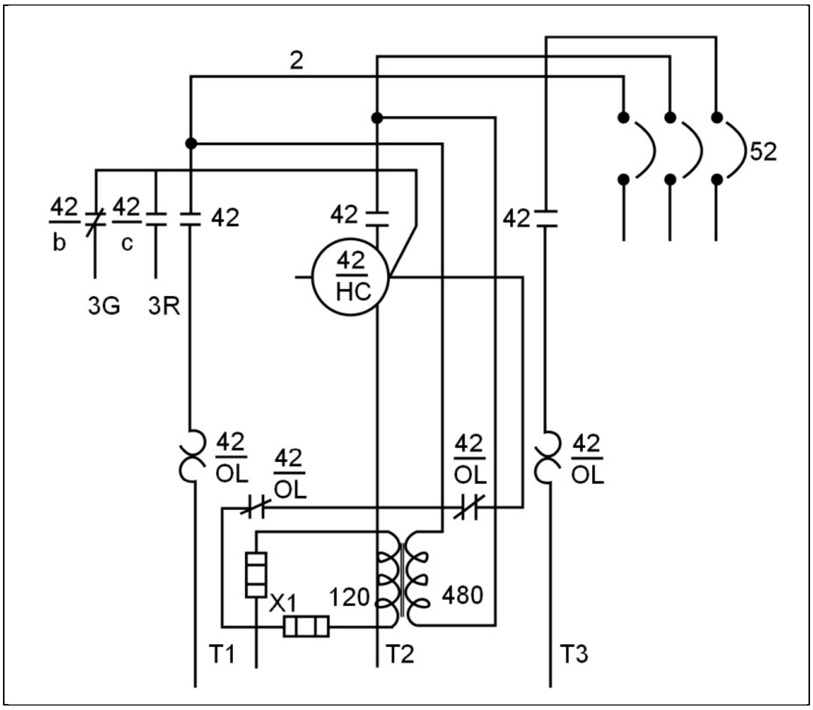


Fig. 2.1-20 Wiring Diagram of the Motor Control Circuit

Wiring diagrams are not usually drawn to scale, so the location of components on the diagram will not necessarily be exact, but relative. However, wiring diagrams do show components in approximately the correct area.

USING SCHEMATICS AND WIRING DIAGRAMS

Troubleshooting process often uses both of schematic and wiring diagrams to locate the components and terminals that have been tested.
The following example illustrates how to use a schematic and a wiring diagram together to troubleshoot an AC motor controller unit using Fig. 2.1-19 & 20.
Assuming that an electrician is in need to find contact 42/b in the motor controller. The general procedure for locating this particular contact may be as follows:

1. Find contact 42/b on the schematic. It is on the same line as the green indicating light. Since this contact is an auxiliary contact operated by the holding coil, it is safe to assume that it is part of the contactor. According to the schematic, contact 42/b is normally closed.

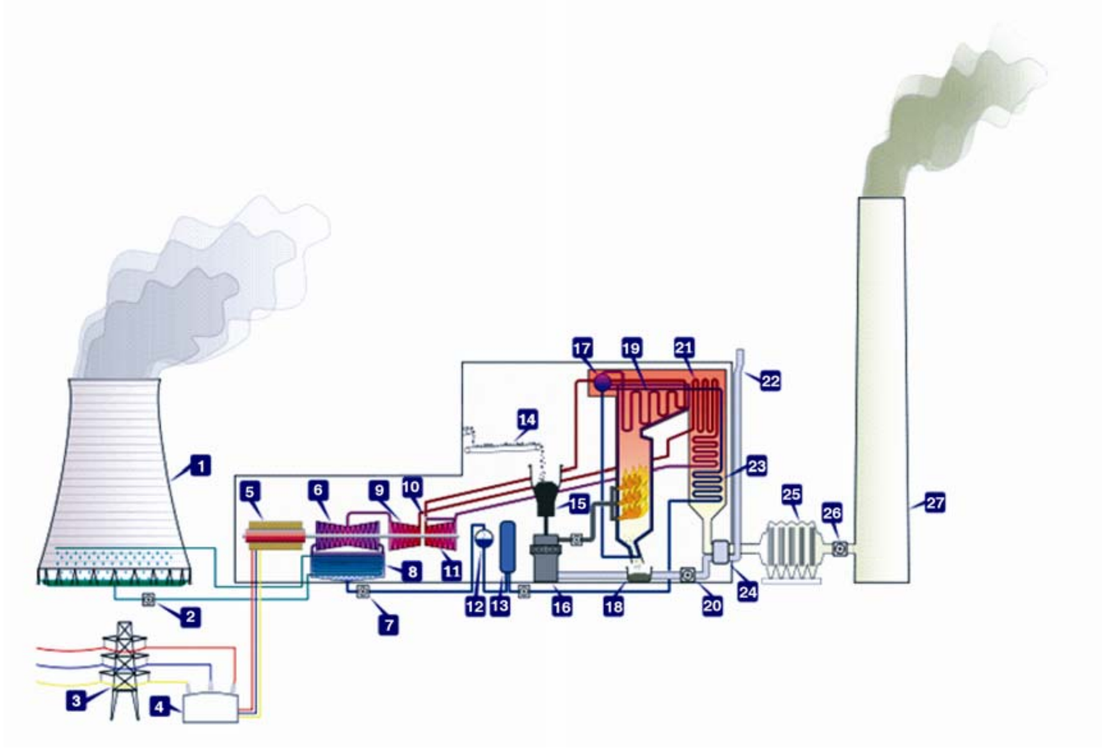
2. Find the holding coil on the wiring diagram and use it as a reference point. The two contacts, one normally open and the other normally closed, are on the left of the holding coil.

3. Refer to the schematic diagram of Fig. 2.1-19 again, and try to find some other reference point to identify the correct contact, positively. One way is to see which contact is connected. On one side of contact 42/b is a junction point labeled 3G. On the other side, the line goes to the set of normally open contacts, to the holding coil, and to the normally closed overload contacts.

4. Go back to the wiring diagram. Find a wire labeled 3G that is connected to a contact and a wire that is connected from the other side of the closed contact to the NO contact, the holding coil, or the overload contacts.

LAYOUT DIAGRAM

Layout diagram determines the exact location of a device/equipment or the components in the circuit.



1- Cooling tower	2- Cooling water pump	3- Transmission line
4- Unit transformer	5- Electric generator	6- Low pressure turbine
7- Condensate extraction pump	8- Condenser	9- Intermediate pressure turbine
10-Steam governor valve	11-High pressure turbine	12-Dearator
13-Feed heater	14-Coal conveyor	15-Coal volatilize
16-Breaker fuel mill	17-Boiler drum	18-Ash volatilize
19-Super heater	20-Withdrawal fan	21-Re-heater
22-Air intake	23-Economizer	24-Air preheater
25-Accelerator	26-Induced draught fan	27-Chimney Stack

Fig. 2.1-21 Power Station Layout Diagram

SUMMARY

1- Block diagram illustrates and simplifies troubleshooting process without worrying about the circuitry details within the block.

2- Single line diagram simplifies three-phase power circuit representing with one single-phase circuit.

3- Schematic diagram describes the details of power system or control circuit.

4- Wiring diagram describes the installation of electric circuit and its labeled terminals.

5- Layout diagram describes the physical location of the components or equipment/device in electrical circuit.

GLOSSARY

Abbreviation:	Identifying letters of a device name
Location:	Place of the components
Label:	Mark or sign, normally number
Layout:	Outline planning showing actual location of equipment/device
Installation:	Assembly for electrical equipment & fitting
Physical:	Material location

REVIEW EXERCISE

1- In order to determine terminal connections of the components, the suitable drawing is:

a- Single line diagram
b- Block diagram.
c- Wiring diagram
d- Schematic diagram

2- In order to determine control circuit details, the suitable drawing is:

a- Single line diagram
b- Block diagram.
c- Wiring diagram
d- Schematic diagram

3- In order to describe three-phase power circuit with simplified drawing, the suitable drawing is:

a- Single line diagram
b- Block diagram
c- Wiring diagram
d- Schematic diagram

4- Schematic diagrams are used to read from ________.

a. right to left and from bottom to top
b. left to right and from bottom to top
c. right to left and from top to bottom
d. left to right and from top to bottom

5- The drawing of Fig. 2.1-22 shows:

a- Single line diagram
b- Block diagram.
c- Wiring diagram
d- Schematic diagram

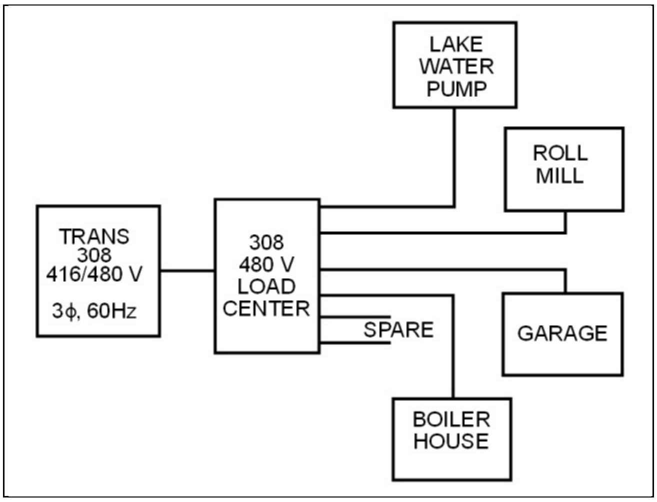
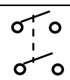
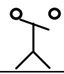
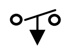


Fig. 2.1-22

Mark True or False:

1.	Power transformer has many standard symbols	
2	Symbols are used to standardize the reading of electrical diagrams.	
3	Symbols show what a component actually looks like.	
4	The fuse is represented by the same symbol in all electrical diagrams.	
5	Wiring diagram usually shows the circuit in the energized condition.	
6	Schematic diagram is used to read from left to right and from top to bottom.	
7	Wires are labeled by numbers for electricians to trace wires in a circuit.	
8	Block diagram can be used instead of wiring diagram	
9	Schematic shows all the components of a unit in their proper physical and electrical positions.	

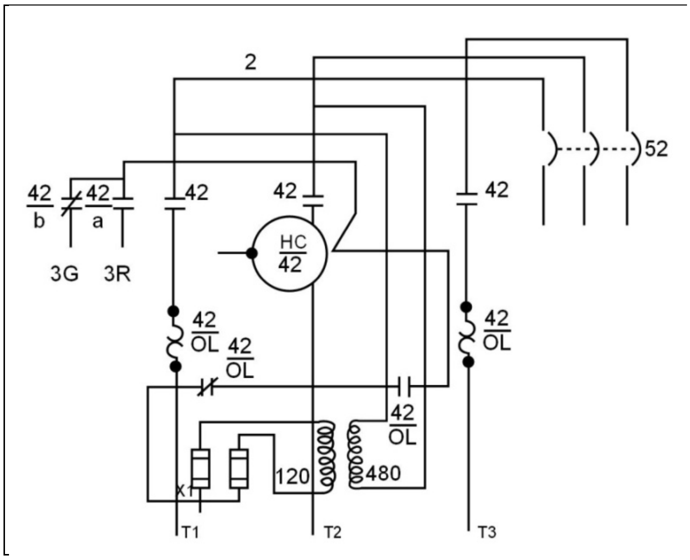
16- Fill-in the blank boxes in the table below, as required:

a) Capacitor (variable)	
b) Fuse	
c) Ground (floating)	
d) Ground (connected)	
e) Conductor crossing (connected)	
f) Potential Transformer	
g)	
h)	
i)	

17- Define the following abbreviations and numbers:

a) HC	
b) GEN	
c) DPDT	
d) NO	
e) 50	
f) 51	
g) 52	
h) 27	
i) 59	

18. Identify the given diagram:



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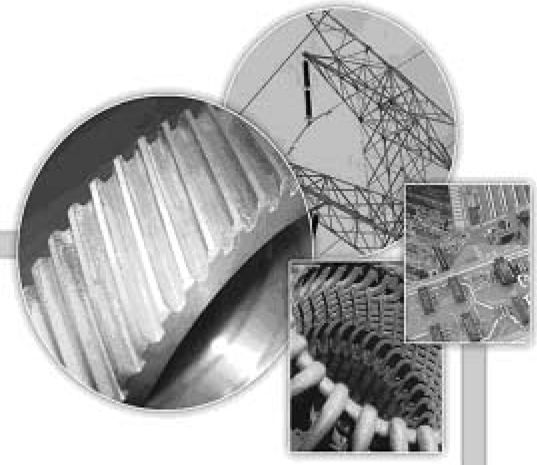


LESSON 2.2

CIRCUIT BREAKERS

LESSON 2.2
CIRCUIT BREAKERS

OVERVIEW

This lesson classifies and describes the different types of circuit breakers. It discusses the main components of circuit breakers and their behavior in closing and tripping operations.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Describe the role of CBs in protective gear.
- Describe the components and operations of bulk and minimum oil CB.
- Describe the components and operations of air blast CB.
- Describe the components and operations of SF_6 gas CB.
- Describe the components and operations of vacuum CB.

INTRODUCTION

Circuit breakers **(CBs)** are used to protect the electrical equipment and circuits against internal or external short-circuit and to provide flexibility of control and operation. Circuit breakers are mechanical devices for opening or closing circuits safely under all abnormal conditions. Circuit breakers can operate automatically as well as manually. For high voltage and heavy current applications, CBs are remote-controlled and are generally spring or electromagnetically operated.
Overload trips, generally with some form of time lag are designed so that the circuit breaker will trip in the event of a serious overload or a fault, as shown in Fig. 2.2-1.

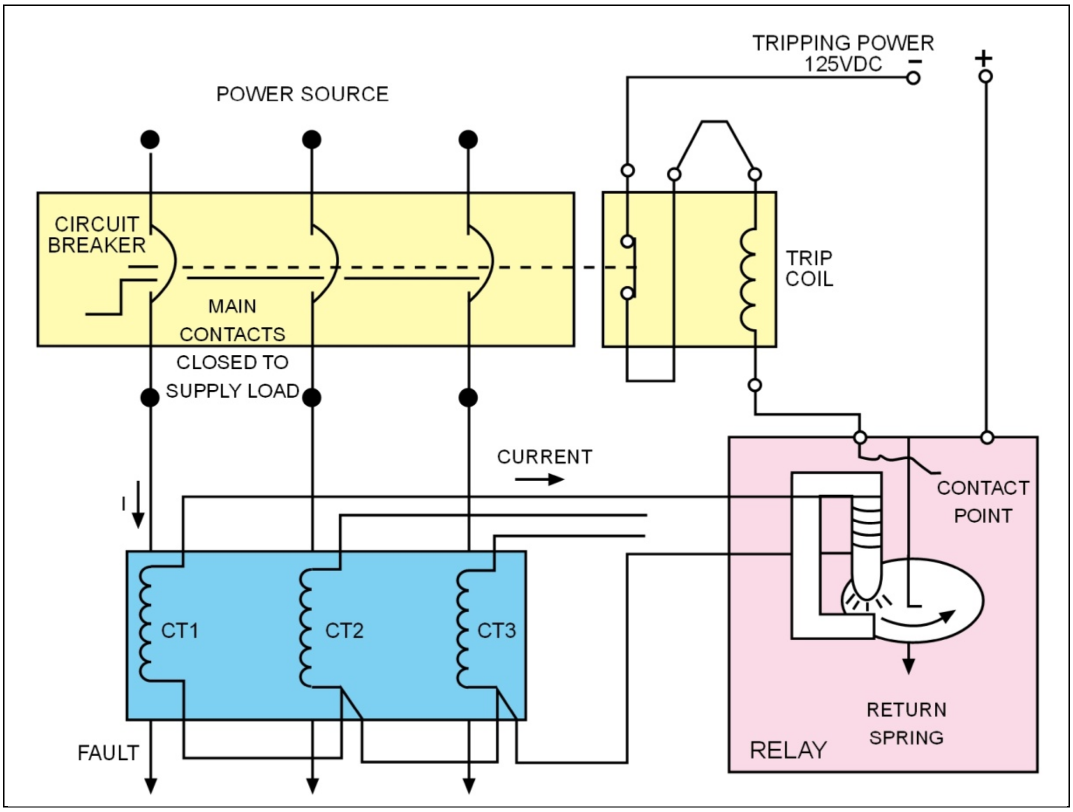


Fig. 2.2-1 Circuit Breaker Configuration with Protection System

Circuit breakers are classified according to insulation and arc extinguish medium. There are Air Circuit Breakers **(ACB)**, Bulk Oil Circuit Breakers **(BOCB)**, Minimum

Oil Circuit Breakers **(MOCB)**, Gas Circuit Breakers **(GCB)**, and Vacuum Circuit Breakers.

RATINGS

Circuit breakers must conform to the particular characteristics of the circuit requirements depending on the applications, they are designed for. The design specifications, therefore, must provide the following:

1. Voltage Rating

a. The nominal kV rating (system voltage)

b. The maximum operating voltage

2. Insulation Class/Level withstanding voltage

It is rated at 60 Hz in RMS kV. This is the maximum voltage that the circuit breaker insulation is designed to withstand.

3. Current rating

Standard current ratings are based on the maximum **RMS** Amperes at 60 Hz that the breaker can carry continuously under usual service conditions without exceeding the temperature limits specified in the NEMA, AIEE, IEC, and DIN Standards.

4. Interrupting ratings

a. Three-phase rated **KVA** or **MVA**

b. Amperes at rated voltage

c. Maximum Amperes

At the time of a short-circuit, the system is not stable, and the voltage at the point of fault may be higher due to lightning or switching surges or lower because of voltage

drops in system conductors. For this reason, the ability of some breakers to interrupt short-circuit currents is expressed in Volt-Amperes. To make the numbers more manageable, larger breakers are rated in kilo-Volt-Amperes **(KVA)** or Mega-Volt-Amperes **(MVA)**.

Tripping time in Cycles

This rating is defined as the time from the energizing of the trip coil with normal control voltage until the circuit is interrupted. Current applied is equal to 25 to 100 % of the interrupting rating.

The magnitude of current flowing in a circuit under normal conditions is determined by the energy demand of the equipment connected to the circuit. This amplitude of current flow is referred to as normal or load current. A short-circuit indirectly disconnects the load and replaces it with almost zero impedance. In this situation, the circuit current is limited only by the impedance of the circuit conductors and transformers from the generation to the point of fault. The resulting fault current can reach extremely high levels and its effects can be very destructive, making it essential to interrupt the circuit as rapidly as possible in order to keep damage to a minimum. Ohm's law clearly demonstrates this situation.

$$I = E / Z$$

Where: I = Current

E = Applied voltage

Z = Circuit resistance

Using this formula for a typical load value,

$E = 2{,}300$ Volts, $Z = 10\ \Omega$

$I = 2{,}300/10 = 230$ Amperes

EXAMPLE 2.2-1

Under short-circuit conditions when the circuit impedance (Z) is only 0.05 Ω at 2300V, determine the short-circuit current.

SOLUTION

E = 2,300 Volts   Z = 0.05 Ω

I = 2,300/0.05 = 46,000 Amperes

If this magnitude of current were to flow through a Circuit Breaker, enormous magnetic forces would be set up between the current-carrying poles and the temperature of the circuit breaker would get extremely high, perhaps high enough to damage the breaker. The high magnetic forces set up by high-level fault currents must be interrupted within a very short time.

BULK OIL CIRCUIT BREAKERS

In the past, BOCB was the most widely used interrupting device for power networks. The insulation and arc extinguishing medium is oil. The breaker consists of three separate large tanks, as shown in Fig. 2.2-2. The operation of BOCB is initiated utilizing direct current by locally or remote operation of supervisory control equipment or relays that automatically recognize electrical failure in the system, as shown in the configuration of Fig. 2.2-1.

Fig. 2.2-2 Bulk Oil Circuit Breakers

When the contacts of an oil breaker separate, two things occur:

First, the oil rushes into the gap and cools the arc. This tends to quench the arc, as shown in Fig. 2.2-3.

Second, the heat and chemical reaction create gases. These hot gases expand rapidly, blowing the arc out, creating great turbulence in the oil, expelling carbon particles that are created, and preventing them from sustaining the arc.

The rate of expansion and the volume of gas generated depend on the magnitude of the short circuit current to be interrupted, the speed of the separation of the contacts, the cooling effect of the oil and the quantity of oil used as the insulating medium. Oil is an excellent dielectric with flash point voltages of approximately 30 kV per 0.1 inch. This fact allows closer clearances in breaker design and, hence, smaller circuit breakers.

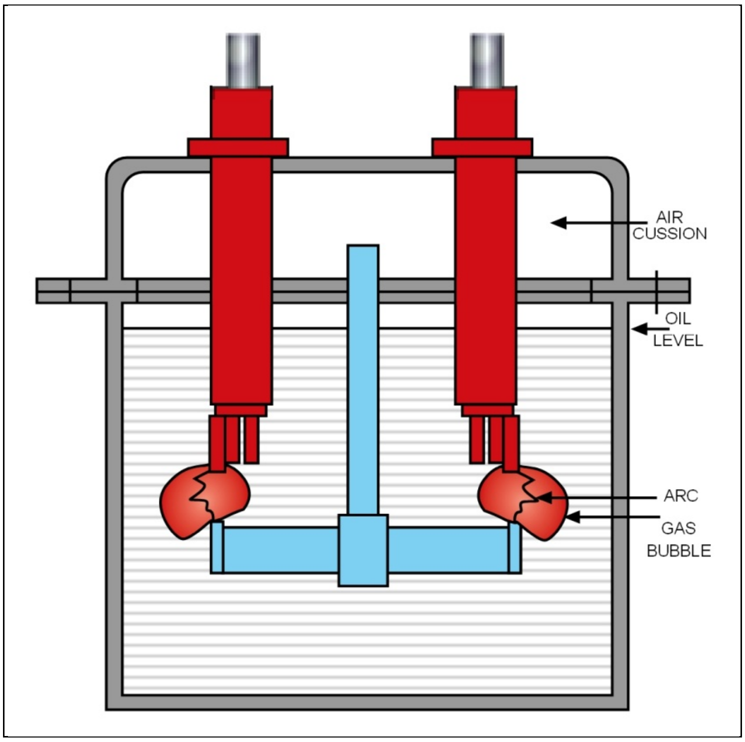


Fig. 2.2-3 BOCB Braking Mechanism

A final advantage of oil as an insulator is its excellent cooling properties. Greater currents may be carried in smaller packages when oil is used as a coolant.

Pneumatically operated OCB quenches the sparks of high voltage better than Air Circuit Breakers

CIRCUIT BREAKER CONTROL PANEL

The control panel is used for mounting the necessary AC/DC control devices, knife switches, thermostat, anti-pump relay, auxiliary switches, servo motor starter, and the test push-button station. The test push button station is used for electrical operation of the breaker from the breaker control panel.

This test switch should not be used unless the reclosing circuit has been opened. The BOCBs are normally opened and closed by control switches in the control room. They can be operated locally at the OCB by putting the selector switch to the local position and operating the control switch. Normally, the selector switch is on remote. Emergency manual trip handle is mounted on left side of mechanism cabinet, as

shown in Fig. 2.2-4. Trip handle can be padlocked either to hold the breaker trip free or to prevent use of external trip handle.

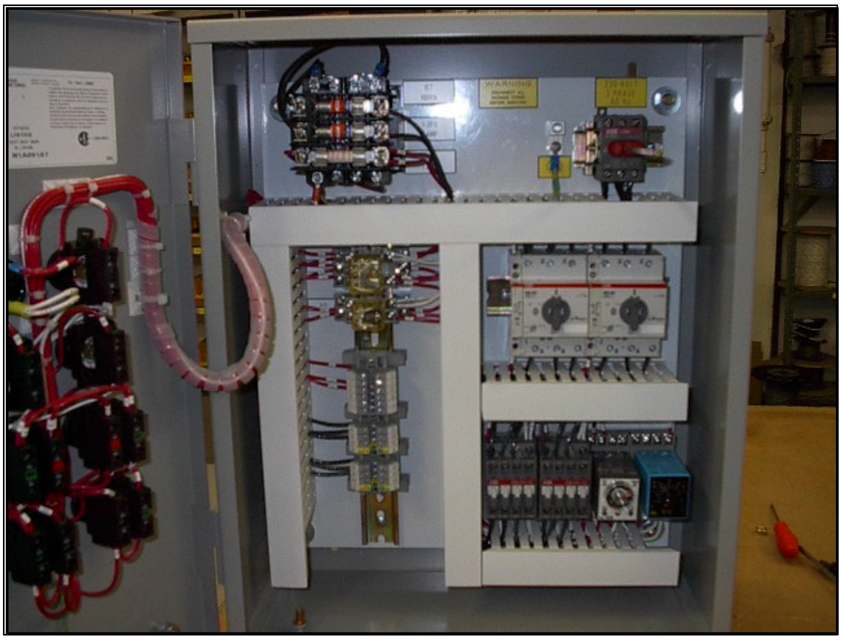


Fig. 2.2-4 Circuit Breaker Control Panel

MINIMUM OIL CIRCUIT BREAKERS

In the MOCB, the tank is a vertical tube of insulating material held between metal and caps. As these caps are the terminal points for the external circuit, the tank in normal circumstances, is live at line voltage. This assembly is designated the circuit-breaking fighting chamber or interrupter head and supported on one or more insulators depending on the design suitable for the system voltage, as shown in Fig. 2.2-5. Operating mechanism of MOCB is mostly spring that can be charged either manually or by a motor. The energy stored in the spring is utilized for both the closing and tripping operations.

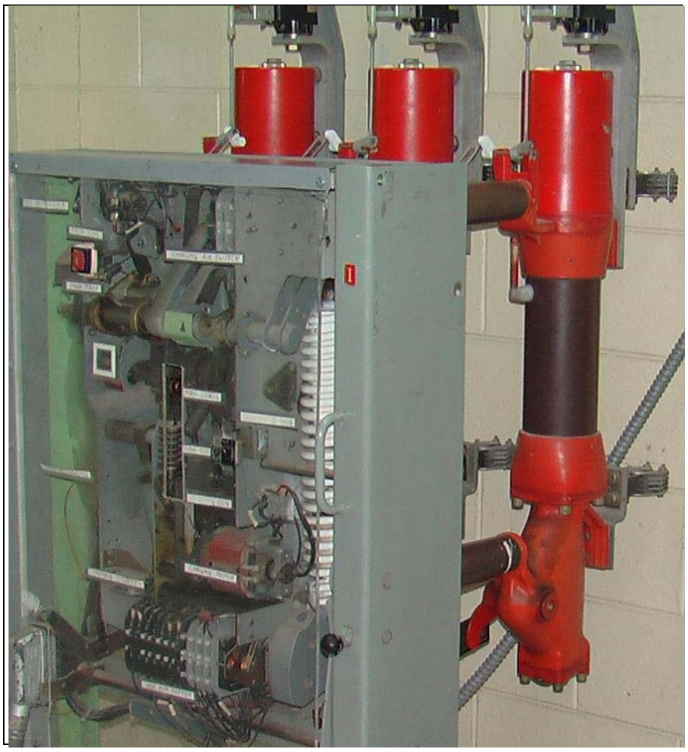


Fig. 2.2-5 Minimum Oil Circuit Breaker

Minimum oil CBs differ from BOCBs in reduced size and oil volume. Fig. 2.2-6 shows comparison between MOCB (a) and BOCB (b). In the BOCB, the tank is "dead" i.e. it is at earth potential and the necessary clearances for the system voltage must be maintained in oil between live contacts and the tank.

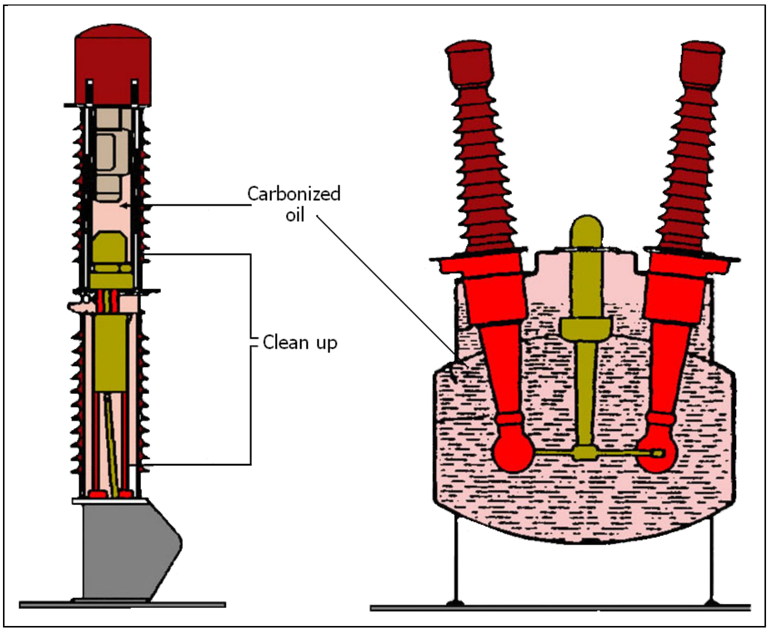


Fig. 2.2-6 Fighting Chamber in the MOCB & BOCB

EXAMPLES OF MOCB

66 kV MOCB type TRI (BBC), as shown in Fig. 2.2-7, is an example of MOCBs, 66 kV, indoor type, carriage mounted, withdrawal with plug in contacts. The breaker is capable of switching a fault current of 31.5 kA. With regard to the circuit breaker poles, the breaker is of the low oil content type, fitted with arcing chamber and oil injection to achieve short arcing times at low current interruption.

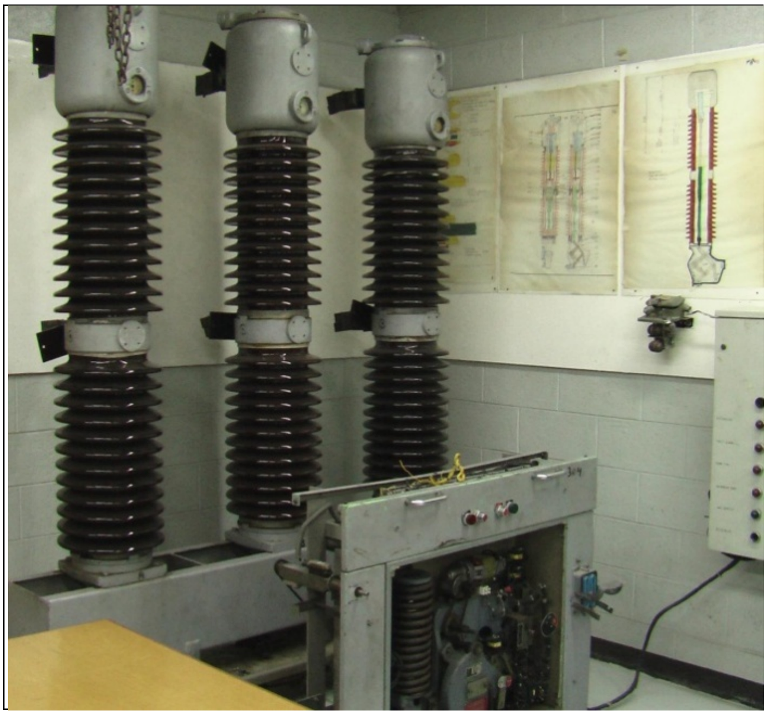


Fig. 2.2-7 MOCB, Type TRI

The spring-operated drive transfers the operating power mechanically to the contacts. The closing spring in the drive housing is normally rewound by motor, or if necessary, by hand, while the trip springs (one assigned to each phase) are automatically charged on release of the closing spring. The mechanism can be released mechanically by means of turning knobs or electrically by means of remote control, respectively. The spring-storage is suitable for one rapid auto-reclosing operation and can perform an open-close-open operation cycle without recharging the spring.
Nominal current of circuit breaker under normal conditions is 1600 A.

AIR BLAST CIRCUIT BREAKER

In ABCB, the current interruption is throttling through a powerful blast of air at high pressure and velocity in the arcing region, as shown in Fig. 2.2-8. For BOCB and MOCB, there is no external aid required for current interruption where as for Air Blast CB, a supply of clean dry air at the correct pressure and in sufficient volume must be available at all times. To accomplish this, compressed air is stored from duplicate compressors in storage facilities with associated network of feed pipes.

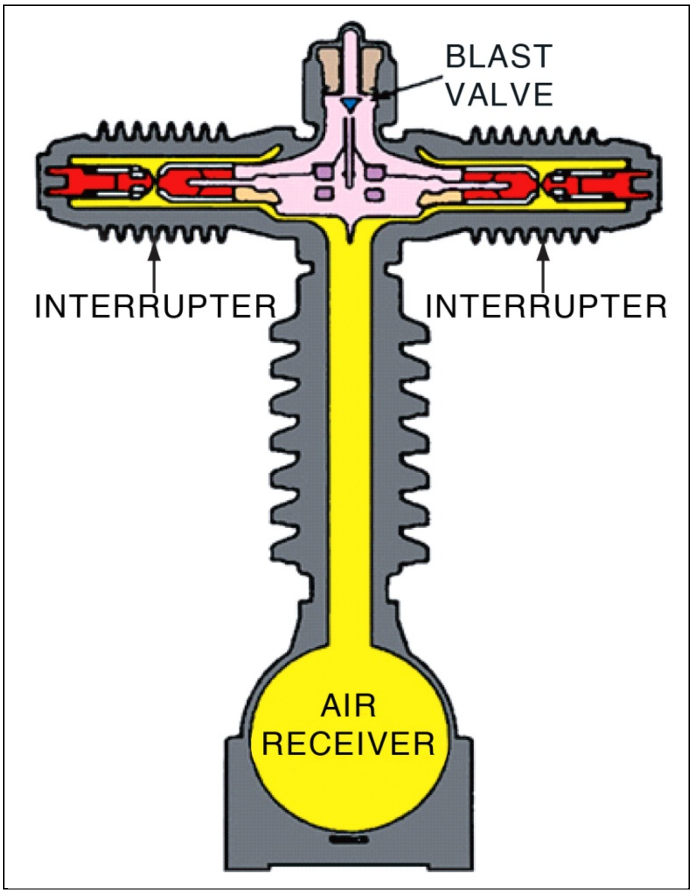


Fig. 2.2-8 Air Blast Circuit Breaker

GAS CIRCUIT BREAKERS

Fig. 2.2-9 shows the construction of a GCB. SF6 gas is used for insulation and extinguishing medium in circuit breakers. SF6 is a colorless, odorless, non-toxic, an inert and odorless gas. It has excellent dielectric properties under comparable

conditions. Its dielectric strength is about 2.5 times that of air. This gas, under pressures (20 to 240 pounds/square inch), extinguishes the arc so rapidly as to almost prevent its formation. It also has excellent heat-dissipating characteristics and its dielectric strength is much greater than that of oil. SF6 breakers use hydraulic mechanisms that are extremely fast and are capable of opening and hydraulically reclosing. Energy from five closures is stored by compressing nitrogen gas in an accumulator. Opening energy is stored in breaker springs during closure.

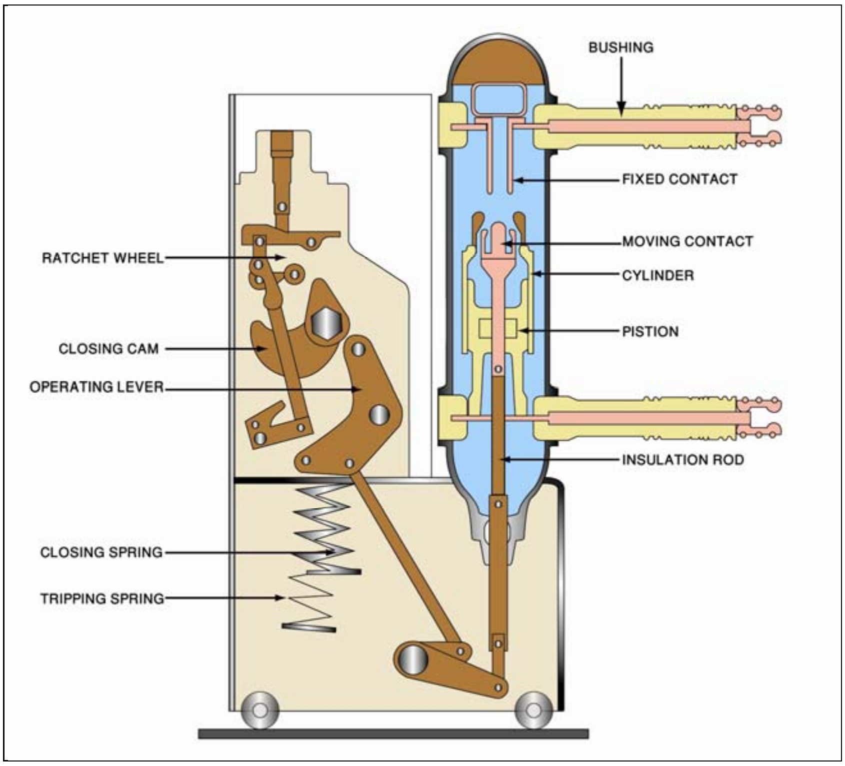


Fig. 2.2-9 Construction of GCB

GAS CIRCUIT BREAKER TYPE 30 SFG (MITSUBISHI)

Gas circuit breaker type 30 SFG shown in Fig. 2.2-10, is withdrawal type filled with SF6 gas. Fig. 2.2-11 shows the gas circuit breaker inside the switchgear and Fig. 2.2-13 shows the parts of the circuit breaker.

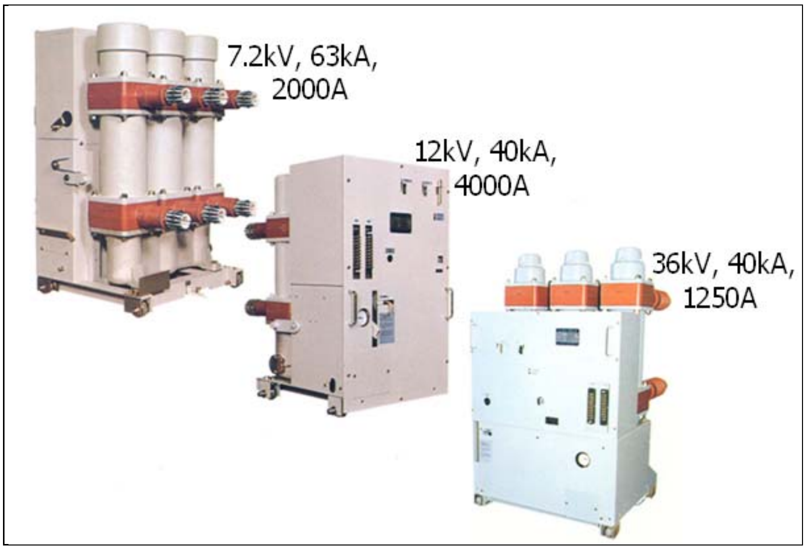


Fig. 2.2-10 Type SFG SF_6-Gas Circuit Breakers

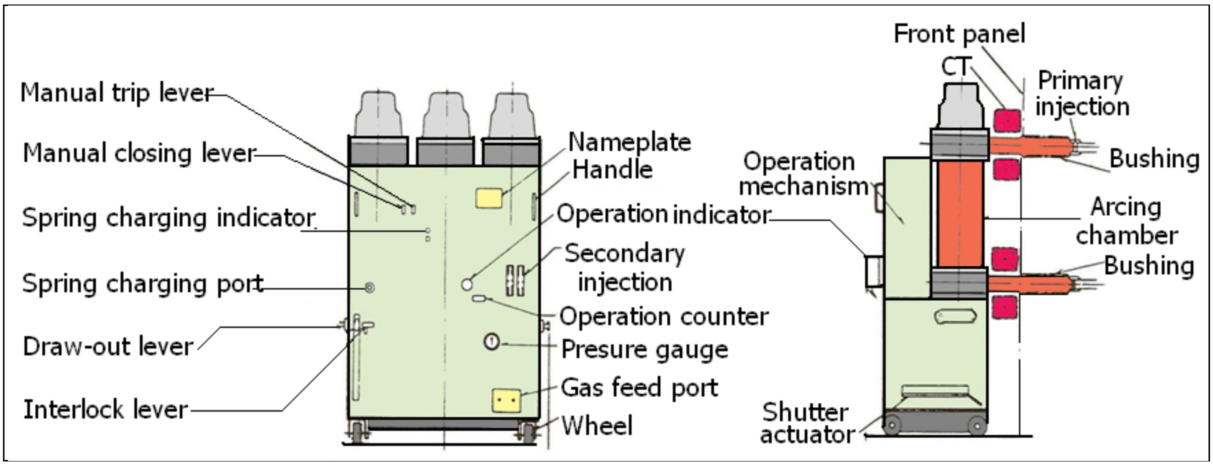


Fig. 2.2-11 Rear-panel & Side view of Gas CB

INTERRUPTING UNIT OF GAS CB

The interrupting unit in Fig. 2.2-12 consists of a fixed contact, a moving contact, a movable cylinder, and a fixed piston. For the interruption of the breaking current, the moving contact opens and then the breaking arc is drawn between the fixed and the moving contacts. At the same time, the cylinder moves and compresses the gas to generate a temporary pressurized gas. This gas puffs (blows) on the breaking arc through the nozzle to extinguish it. This is the principle of the puffer-type interrupting unit.

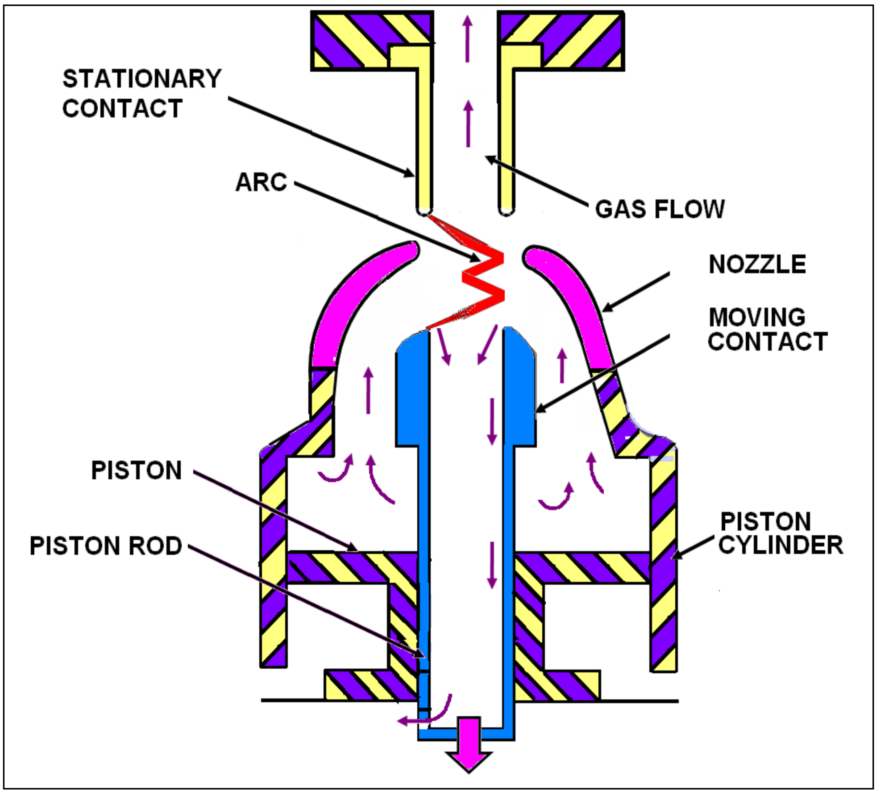


Fig. 2.2-12 Interrupting Unit

ARCING COLUMN

The interrupter is a single pressure type that consists of cylinder and a piston, as shown. The arcing chamber of each pole unit consists of a cylindrical arcing tank and two bushings comprising a pressurized chamber as a whole.

OPENING OPERATION

At the opening operation, the insulation rod moves downward and the piston rod go down together with the cylinder and moving contact. Then the moving contact separates from the fixed contact and the breaking arc is drawn between the arc contact and the fixed contact. At the same time, SF6 gas in the space "A" of the cylinder is temporarily compressed to flow out through the holes at the upper end of the cylinder. The pressurized gas through the nozzle quenches the breaking arc.

CLOSING OPERATION

At the closing operation, fresh gas is drawn into the cylinder on the upward movement of the cylinder. An insulation rod is provided in the bottom casing. At the bottom of the rod, there is a set of sliding seals to transfer the operating force from the closing mechanism to the interrupting unit in SF6 gas.

OPERATING MECHANISM

The operating mechanism is a spring mechanism, shown in Fig. 2.2-13, mounted on a draw-out carriage.

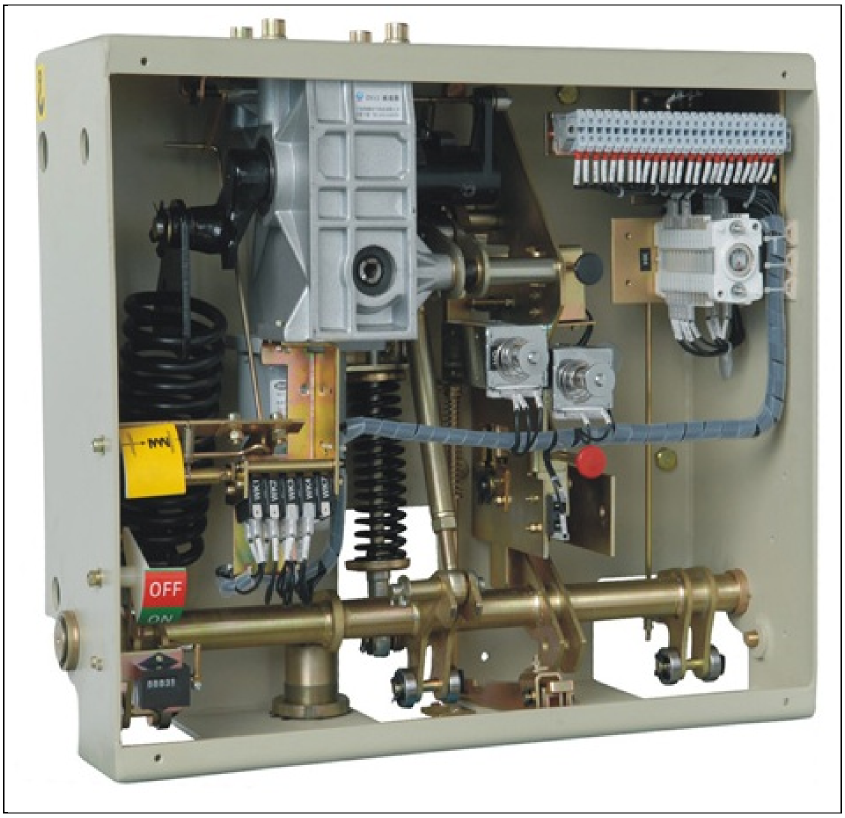


Fig. 2.2-13Operating Mechanism

Sufficient energy for one closing operation is stored by charging the closing spring by means of either an electric motor or manual crank handle. With the spring loaded, the breaker can be closed and opened either mechanically or electrically.

TRIPPING

The breaker can be tripped by pulling up the tripping trigger shown in the drawing and during the fault, tripping coil will pull up this trigger.

BREAKER INTERLOCK SYSTEM:

Interlock for Projection of Connections to secondary Junction. There is an interlock system to protect the connection and withdrawing the breaker as shown in Fig. 2.2-14, the interlock located beside the withdrawal carriage lever. Breaker is removeable by withdrawal and interchangeable for faster and easier replacement during maintenance. The circuit breaker is fully interlocked to ensure that faulty switching is impossible during insertion or withdrawal.

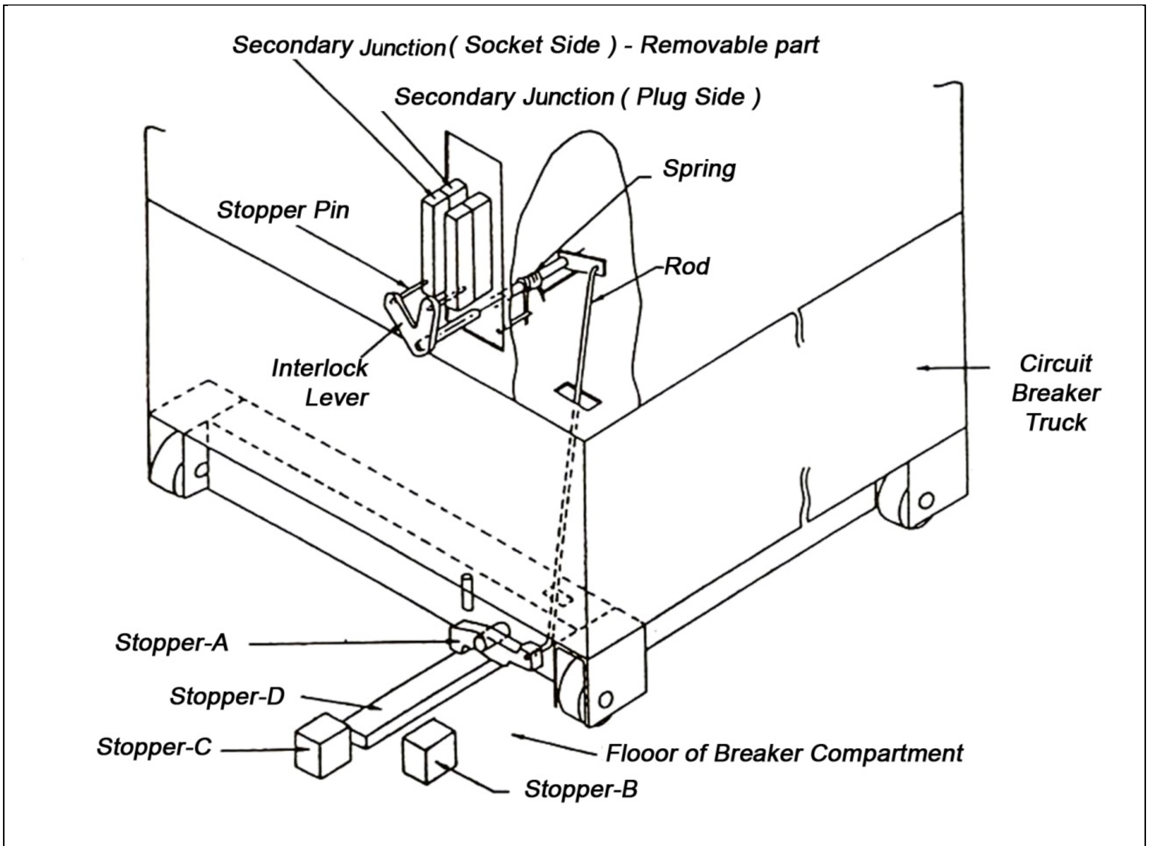


Fig. 2.2-14 Interlock for Secondary Junction Connection

Since SF_6 gas is physically non-toxic and non-combustible and there is absolutely no insulating oil present, there is no danger to personnel and no fire hazard. Since no gas exhausts from the breakers and no compressed air is required in operation.

VACUUM CIRCUIT BREAKERS

A vacuum CB is used in high voltage distribution circuits. The contacts are in vacuum in a sealed container in the form of flat disks with their faces together, as shown in Fig. 2.2-15

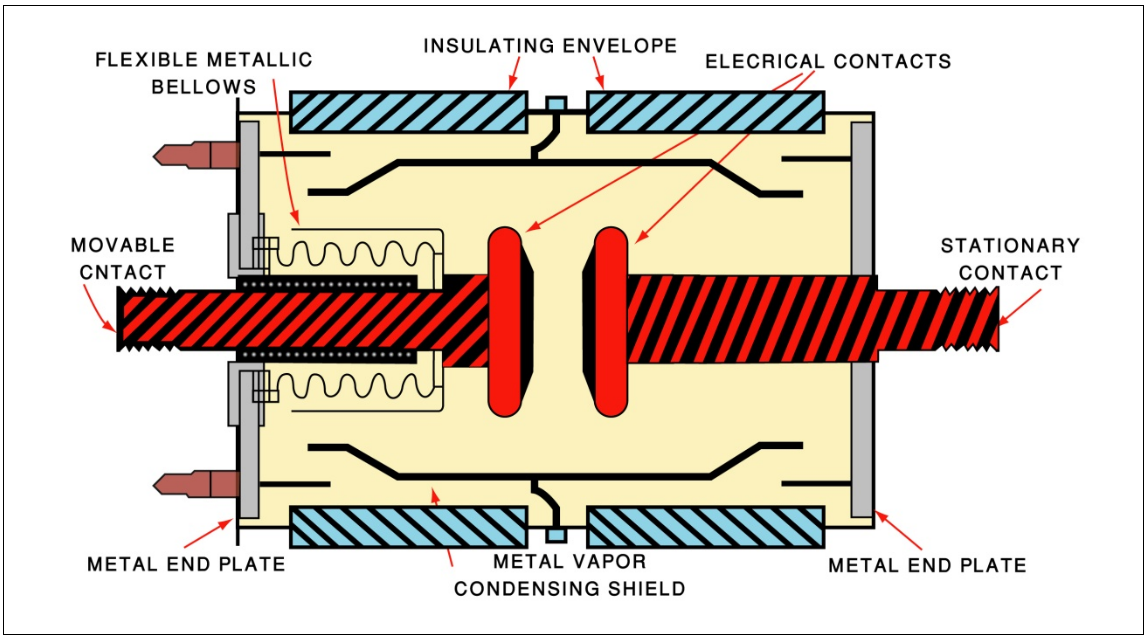


Fig. 2.2-15 Vacuum Circuit Breaker

The moving contact is connected to the outside operating mechanism by means of metal bellows to maintain the vacuum. Since the contacts are in a vacuum, there are no particles to cause ionization when the arc is formed as the contacts part. However, some ionization occurs at the contact surface, owing to vaporized metal at this point, but the arc is extinguished at the first current zero after the contacts start opening. Thus the duration of the arcing time is very short, there is no oxidization of the contacts, contact burning is negligible, and since they are in a vacuum, the contacts require no maintenance.

A vacuum does not dissipate heat as readily as other insulating media. Although this type of breaker has certain advantages in terms of its size and simplicity, its interrupting ratings are not comparable to those of Oil Circuit Breakers. Fig. 2.2-16 shows example of a VCB.

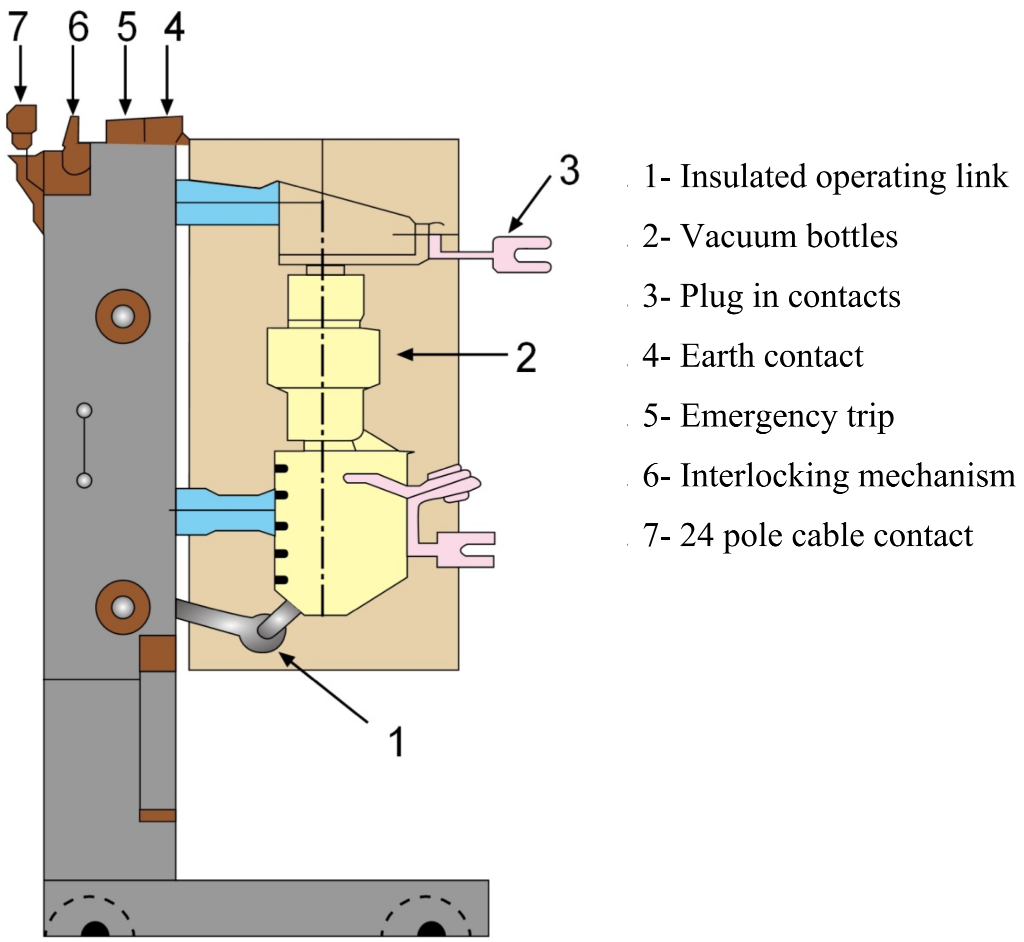


Fig. 2.2-16 Vacuum Circuit Breaker

SUMMARY

- Circuit breaker is a member of the protection system to ensure tripping when fault occurs.
- Circuit breaker has the ability to trip under high short circuit current.
- Circuit breaker has a fighting chamber and high speed mechanism that operates during close and trip.

- Bulk oil CB has fixed large tanks filled with oil.
- Minimum oil CB has little tank in size and less oil volume.
- Air blast CB is provided with compressed air tank to extinguish the fire produced during trip operation.
- SF6 CB is provided with SF6 gas in its fighting chamber to extinguish the arc produced during trip operation.
- Vacuum CB is provided with isolated chamber per phase that is empty from air.

GLOSSARY

Fighting chamber:	Closed small room to extinguish arc during trip
SF_6 gas:	Salver hexa fluoride gas
Bulk oil:	Big in size/large quantity of oil
Minimum oil:	Small in size/ little quantity of oil
Vacuum:	Empty from medium
Air blast:	Blowing compressed air
NEMA:	National Electrical Manufacturers' Association
Arc chutes:	Separators directing the arc

REVIEW EXERCISE

- List four types of Circuit Breakers according to quenching medium:

  a) b)

  c) d)

2. Under the condition of short-circuit condition drawing 2000A current from a 13.8kV line voltage, the short-circuit impedance (Z) is _________ Ω.

   a) 6.9 b) 69

   c) 2k d) 13.8

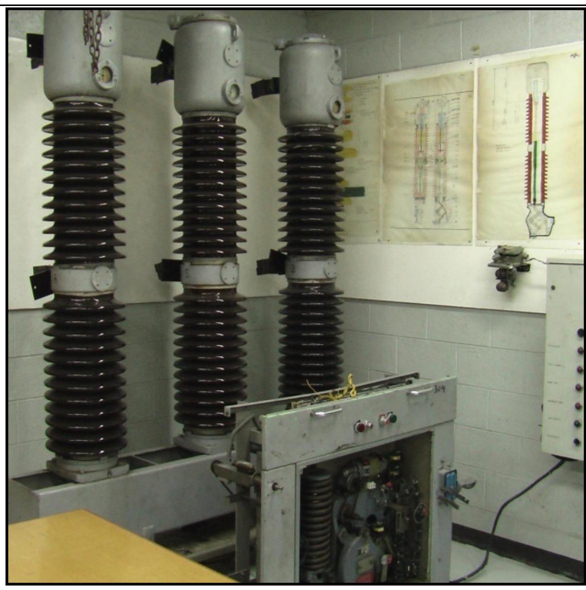
3. OCBs suppress the arcs better than Air blast Circuit Breakers.

   a) True b) False

4. All tanks in BOCB are mounted directly to the floor without insulators and grounded at 0V potential.

   a) True b) False

5. Identify the following circuit breakers:



________________________________ ________________________________

6. A ____________ is used in high voltage distribution circuits where the contacts are in the form of flat disks with their faces together in a sealed container empty of medium.

7. Operating mechanism of MOCB is mostly _______, that can either be charged manually or by a motor and the energy stored in the _______ is utilized for one closing and tripping operations.

TASK 2.2-1

MINIMUM OIL CIRCUIT BREAKER

OBJECTIVE

Upon completion of this task, the participants will be able to:

- Demonstrate the operation process (close & trip) of minimum oil circuit breaker.

TOOLS, EQUIPMENT & MATERIALS

1- Minimum oil circuit breaker

PROCEDURE

1. Go with your instructor to the minimum oil circuit breaker.
2. Visually inspect the minimum oil circuit breaker.
3. Look at the front panel and inspect control switches.
4. Identify the rear panel, fighting chambers, and control spring.
5. To switch the breaker "ON," press the pushbutton (I).
6. To trip the breaker manually, push the pushbutton (0).
7. To charge the closing spring manually, push the slide on the front plate towards, the left-hand side and insert hand tube on to the visible tank and charge with an upward-downward movement.
8. Ask your instructor to check your work.

TASK 2.2-2

POSITION CHECK OF SF_6 CIRCUIT BREAKER

OBJECTIVE

Upon completion of this task, the participants will be able to:

- Check the position of the circuit breaker and rack it out, in, or to the test position.

TOOLS, EQUIPMENT & MATERIALS

- SF6 Circuit Breaker

PROCEDURE

A. RACKING OUT THE CARRIAGE FROM THE SERVICE TO TEST POSITION

1. Trip the breaker.
2. Bring the draw handle and fix it in position.
3. With the left hand pressing gently on the draw handle downwards, press the interlock lever with the right hand to the right direction, the interlock is released.
4. Continue pressing the draw handle with the left hand downwards while drawing out the carriage until a sound is heard and it reaches the test position label and stopped. Now the CB carriage is in the test position and the test switching on and off can be carried out.

B. RACKING OUT THE CARRIAGE FROM THE TEST TO DISCONNECT POSITION.

1. Make sure that the breaker is tripped.

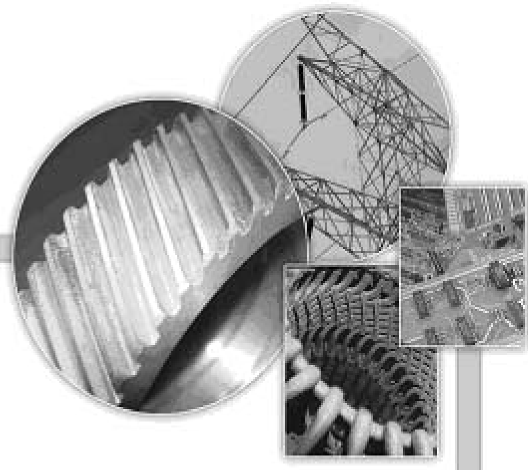
2. Bring the carriage tray and put it in the correctly aligned position to receive the carriage.
3. Disconnect the carriage low voltage DC plugs and maneuver the carriage by hand to bring it out of the cubicle (on the tray).
4. Now the breaker is in the disconnect position and ready for maintenance operations.

C. RACKING IN THE CARRIAGE FROM DISCONNECT TO TEST POSITION

1. Make sure that the breaker is tripped.
2. Bring the carriage on the tray. Align the carriage by means of the guide rollers with the guide rails of the cubicle. Maneuver the carriage by hand to push it into the cubicle.
3. Rack-in the carriage in the cubicle till the carriage interlock lever drives into the guiding grooves in the cubicle.
4. Connect the carriage low voltage DC plugs. Now the CB carriage is in the test position and test switching on and off can be carried out.

2. RACKING IN THE CARRIAGE FROM THE TEST TO THE SERVICE POSITION

1. Make sure that the breaker is tripped.
2. Fix the draw handle in its position.
3. With the left hand pressing gently on the draw handle upward, press the interlock lever with the right hand to the right direction to release the interlock.
4. Continue pressing the draw handle with the left hand upward, while pushing in the carriage with the right hand till a sound is heard and the carriage is stopped inside the cubicle (interlocked). Now the CB carriage is in the service position and the breaker can be operated.



LESSON 2.3

CIRCUIT BREAKER CONTROL CIRCUITS

LESSON 2.3

CIRCUIT BREAKER CONTROL CIRCUITS

OVERVIEW

This lesson discusses the requirements of controlling CB, the limitation interlock of close operation, using schematic diagrams to identify and troubleshoot the control circuits.

OBJECTIVES

Upon completion of this lesson, the trainee will be able to:

1. Describe elements of the control circuit.
2. State functions of auxiliary switches.
3. Describe control circuit operation using schematics.
4. Read control circuits for S&S Minimum Oil Circuit Breaker.

INTRODUCTION

Circuit breaker is the action element of the protection system. It receives the protection signal from the relay and applies the trip action as an automatic operation. Both of close and trip operations can be verified either manually from local push button on the breaker front panel or remotely from the control room.

The mode of operation can be selected on the breaker control circuit drawing. Closing or tripping operation depends on a certain mechanism. That mechanism may be either a solenoid with a plunger acting directly on the mechanism latch or in the case of an air-blast pneumatically operated breakers, an electrically operated valve. The relay may energize the tripping coil directly, according to the coil rating, and the number of circuits to be energized through another multi-channel auxiliary relay. The power required by the trip coil of the circuit breaker may range from 50 watts, for a small distribution circuit breaker to 3000 watts for a large extra-high-voltage circuit breaker.

The basic trip circuit is simple, using a manual control switch and the contacts of the protective relays in parallel to energize the trip coil from a battery, through a normally open, auxiliary switch operated by the circuit breaker. This auxiliary switch trips the circuit when the circuit breaker opens, since the protective relay contacts are usually incapable of performing the interrupting function. The auxiliary switch is adjusted to close as early as possible for effective protection in case the breaker closes due to a fault.

A control battery provides the most reliable tripping source, supplying power to the shunt-trip through the protective relay contacts. The circuit breaker opens the trip circuit through the interconnected auxiliary switch.

When Breaker opens, the Auxiliary Switches keep the trip Coil open to prevent burning of the Relay Contacts. The circuit breaker, protective relay, and instrument transformers are all part of the protection system, as shown in Fig. 2.3-1.

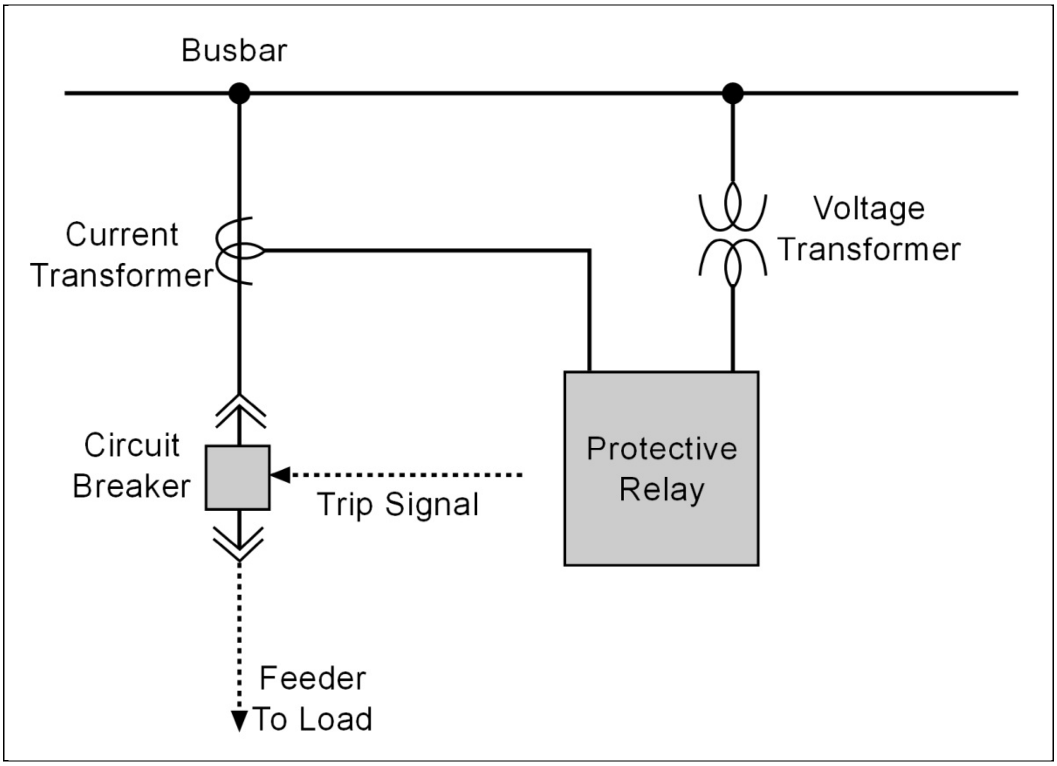


Fig. 2.3-1 Protective Relay and Circuit Breaker

AUXILIARY SWITCHES

Auxiliary switches are front panel connected with two or more poles, double-break rotary contacts. They are available as two, four, six, or eight contact units, and are usually mounted on circuit breakers or other devices.

Two Poles Three Poles Ten Poles

Fig. 2.3-2 Auxiliary Switches

The auxiliary switch actuates through a crank, mounted on the switch shaft, and an adjustable linkage to the circuit breaker. The crank and linkage are designed so that the opening and closing of the circuit breaker rotates the switch shaft. This rotation of the shaft opens the Normally Closed (N/C) "b" contacts when the breaker closes and closes the Normally Open (N/O) "a" contacts. The contact operation is reversed as the circuit breaker opens, that is, the "b" contacts close and the "a" contacts open.

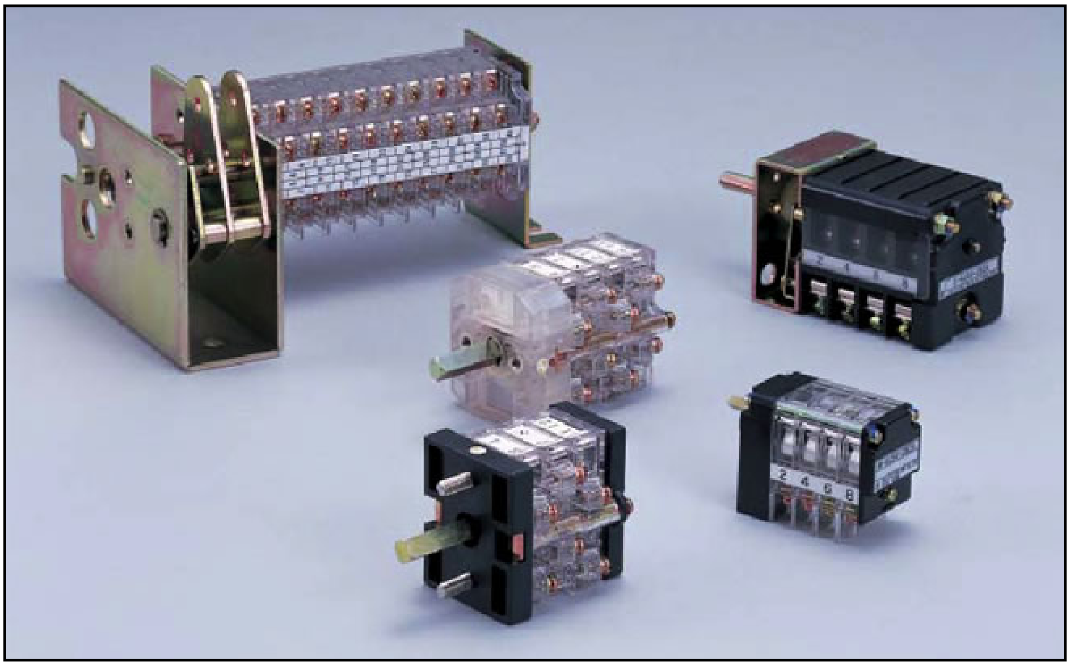


Fig. 2.3-3 Many Poles Rotary Auxiliary Switches

RELAY TERMINAL DIAGRAM

The relay terminal diagram shows in straight-lines form, all circuit and device elements of equipment and its associated apparatus or any clearly defined portion thereof, such as contacts, coils, resistors, etc. Where the inherently designed circuit functions are in a definite sequence, they show all equipment/device elements and their associated circuits. For instance, the overcurrent with earth fault relay and its associated circuit breaker trip circuit is shown in Fig. 2.3-4.

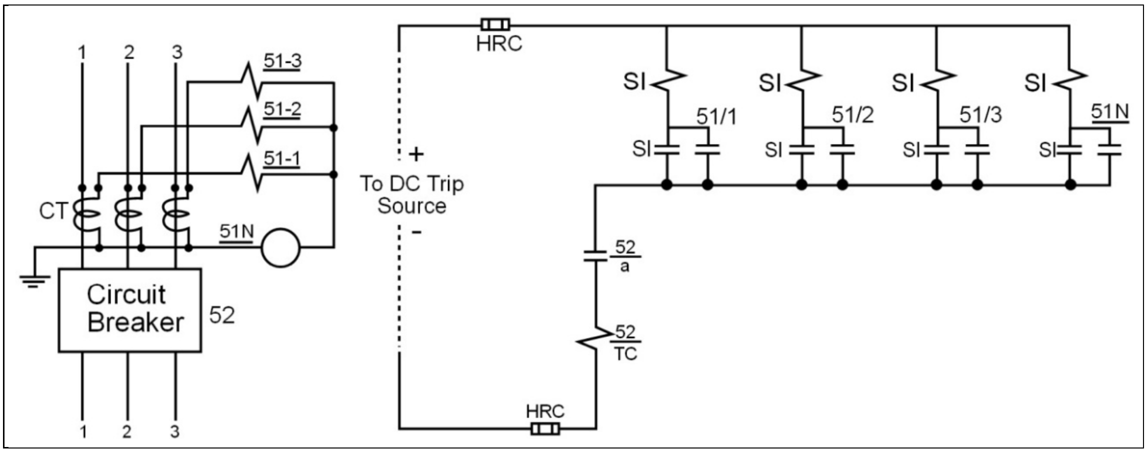


Fig. 2.3-4 Overcurrent with Earth Fault Relay Connection Diagram

The devices are designated by the American Standard Device Function Numbers. Description of auxiliary devices with suffixes X, Y, and Z indicate the nature of auxiliary function, for example:

52X = Closing relay for 52

52a = Auxiliary switch open when 52 is open

52b = Auxiliary switch closed when 52 is open

52CS = Control switch for 52

The function numbers of device elements (contacts, coils etc) label the device elements in most drawings and descriptive abbreviations are located at the bottom of the devices in control panels.

Fig. 2.3-5 Auxiliary Relays and Contacts used in Control Circuits

The abbreviations for control devices are indicated as shown in Fig. 2.3-5:

A = Automatic

RC = Restraining coil

TC = Trip coil

TDC = Time delay closing

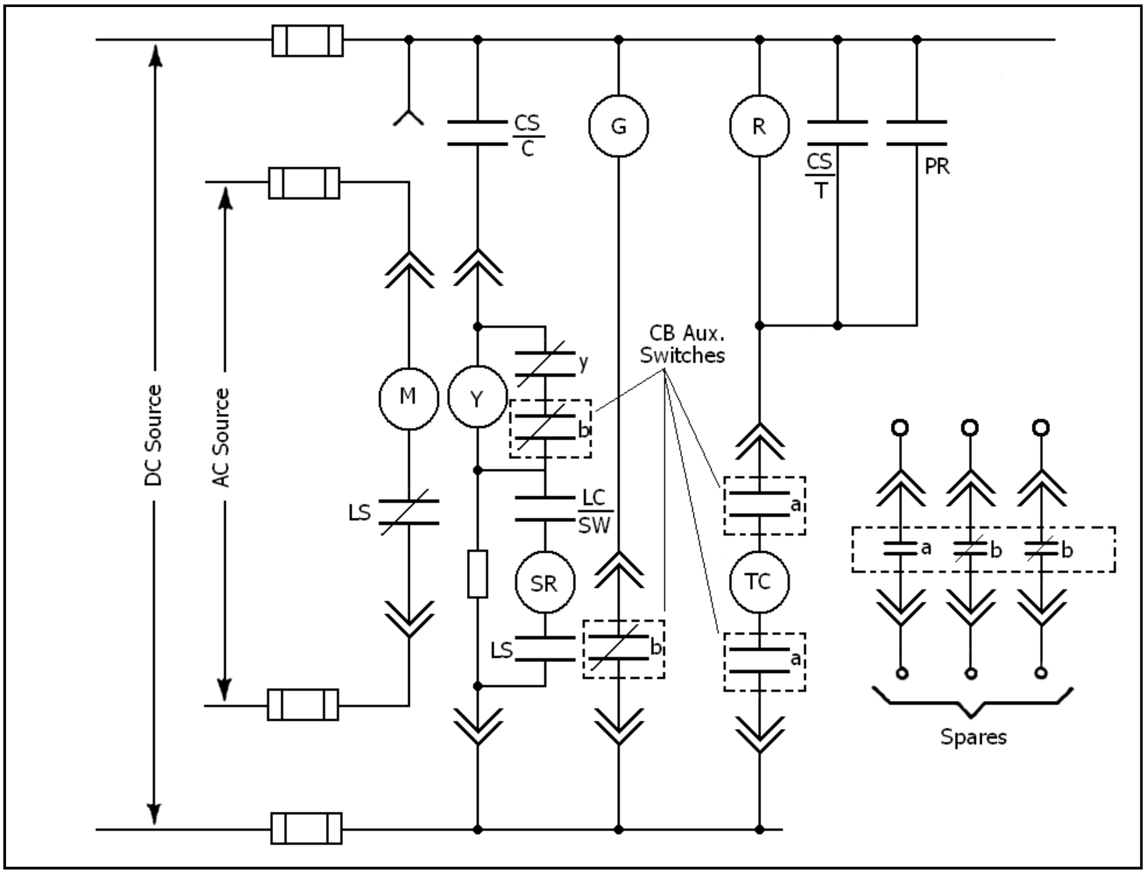


Fig. 2.3-6 Circuit Breaker Control Circuit

TC	Trip Coil	LC	Latch check
Y	Cutoff anti-pump relay	CS/C	Control switch contact for close
LS	Limit Switch	M	Motor
SR	Close Coil	G & R	Green & Red indicating lamp

CONTROL CIRCUIT FOR CIRCUIT BREAKER

Remote close and trip, automatic reclosing, trip free operation, anti-pump operation, and other such features all contribute to the complexity of the breaker control circuit. Fig. 2.3-7 shows a typical circuit breaker closing circuit and Fig. 2.3-8 shows a typical tripping circuit.

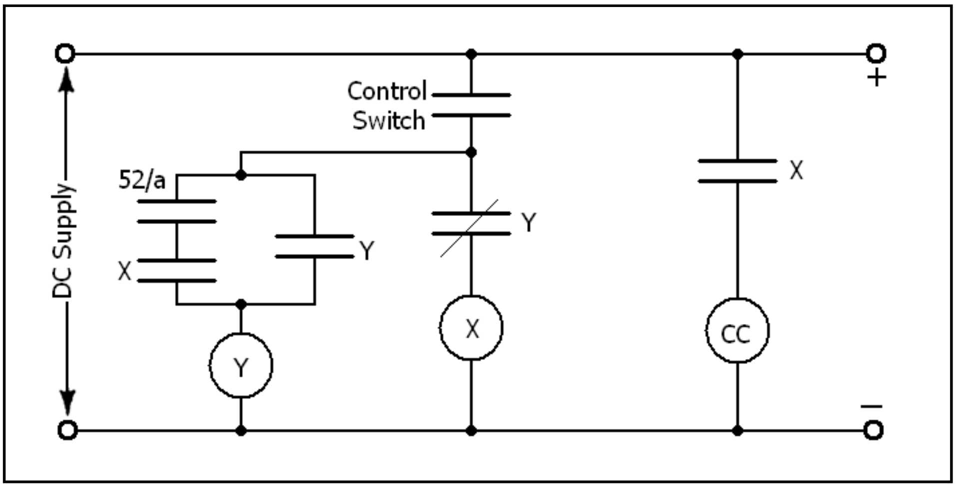


Fig. 2.3-7 Typical Closing Schematic

Operation of the closing circuitry is equally simple as shown When the control switch contact is closed, it energizes the X coil through the normally closed Y contact. The X contact energizes the closing coil (CC), which closes the breaker. When the 52/a switch close, the Y relay is energized through the X contact and the 52/a contact. The Y contacts change state, which de-energizes the X coil and seals in the Y relay through the control switch. As long as the control switch is held in the closed position, the Y relay stays energized and prevents another close. Thus, only one close per turn of the control switch is allowed. This feature is called <u>anti-pumping</u>.

To trip the breaker, as shown in Fig. 2.3-8, when the time overcurrent contact (51) or the instantaneous overcurrent contact (50) close, it will energizes TC through the 52/a contact ("a" contacts close when the breaker closes and open when the breaker opens. "b" contacts are the opposite of the "a" contacts). If the time overcurrent contact initiates the trip, the Seal In (SI) coil energizes and operates the SI contact, and thereby, sealing in the trip circuit to relief the spring of the induction disc relay. As soon as the breaker trips, the 52/a switch opens and resets the trip circuit before the seal-in contact opens. Instantaneous overcurrent relay does not need seal-in because it is not of induction disc type.

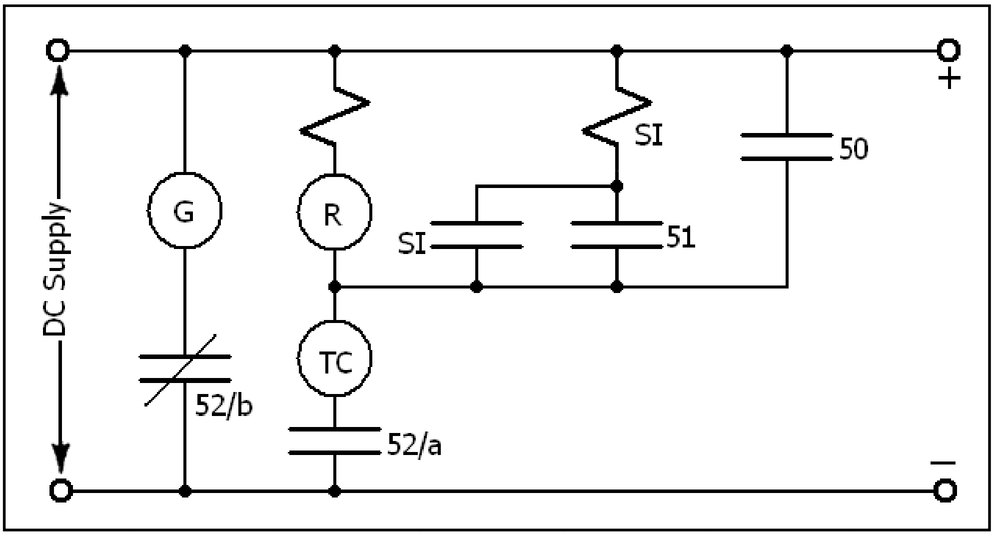


Fig. 2.3-8 Typical Tripping Schematic

TRIP-FREE

A breaker feature to prevent unwanted breaker closing is the trip-free feature. This feature is similar to an electrical anti-pumping with the exception that the mechanism is "free" to move. The mechanism does not operate. However, latch closes and contact motion stops short of closure since a trip is applied to the breaker. A trip-free operation for a pneumatically operated breaker is described below.

The mechanism is pneumatically trip-free at any point in the closing stroke, or at the end of the closing stroke. It is electrically trip-free only when the "AC" switch (not shown) is closed. This switch interrupts the trip coil circuit after a tripping impulse and does not close until the breaker contacts are only a few inches from fully closed, hence, a trip-free operation cannot occur except when the mechanism is nearly in fully closed position.

EXAMPLES TO C.B. CONTROL CIRCUITS READING

Fig. 2.3-9 & 10 show the schematic and schematic diagrams respectively to be used for understanding the operation of close and trip the circuit breaker, either manually or automatically.

CLOSING CIRCUIT BREAKER, LOCALLY

Breaker closing is accomplished by pressing pushbutton (I), manually. To close the breaker locally the selector switch must be in local position (L) and control selector switch in closed position I, so that the closing coil is energized. The contacts SE-38 in A2 are closed when CB is in off position and limit switch contacts 3-3A in A1 are closed when closing spring is fully charged. After closing, the motor starts again to rotate controlled by limit switches (contacts (A1-1, M), and (A1-2, M), as shown, so that the closing spring can be compressed for next closing.
To close the breaker remotely, the selector switch must be in remote position I and all the other closing conditions are met.

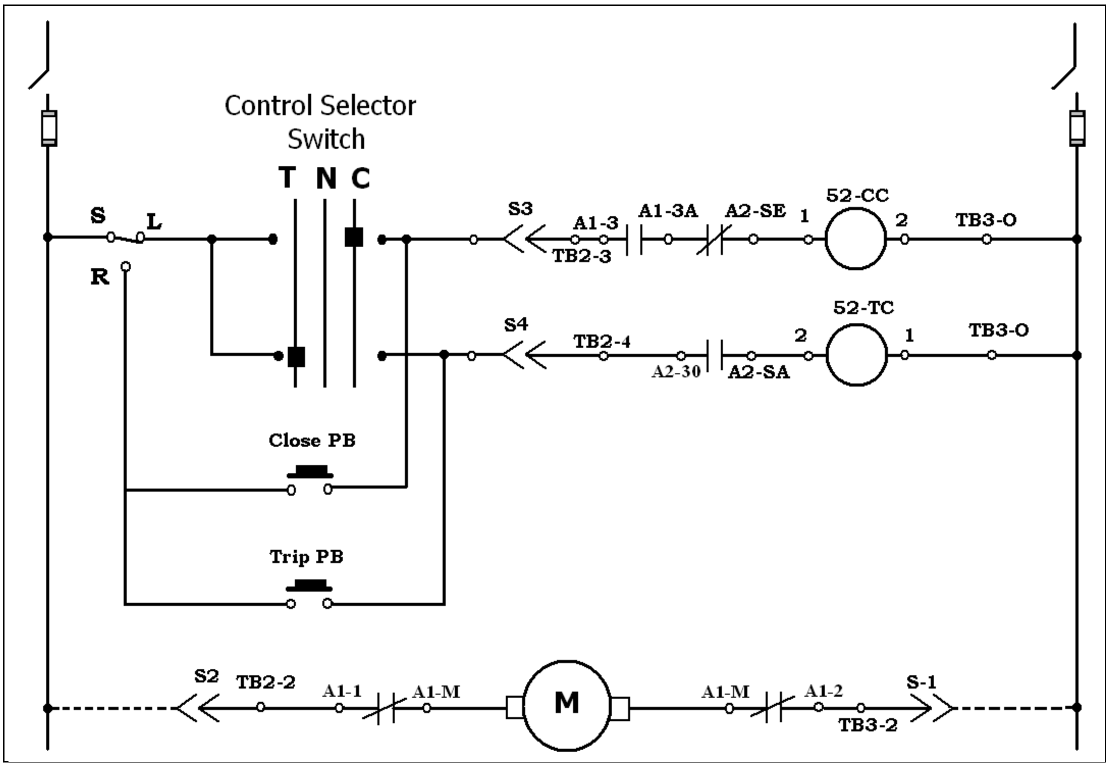


Fig. 2.3-9 Schematic Diagram of S&S CB

TRIPPING CIRCUIT BREAKER

Control selector switch must be turned to position (T). The Tripping Coil (TC) will be energized only if the contacts ($A_2 - S_A$) in aux. switch are closed. The tripping signal

energizes the tripping coil. The trip latch is released and the breaker contacts are opened.

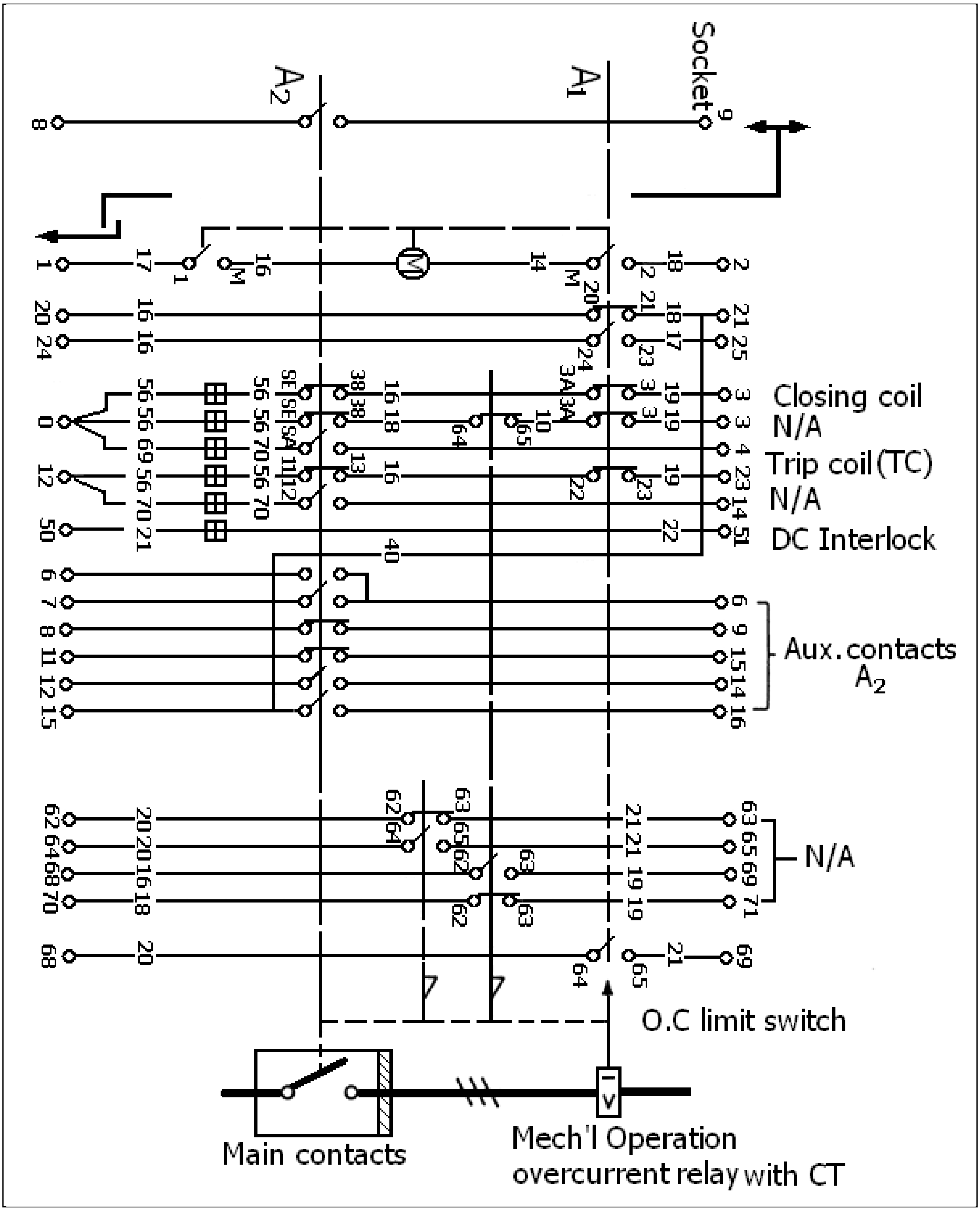


Fig. 2.3-10 Wiring Diagram for S & S CB

3. CONTROL CIRCUIT FOR 69KV MOCB

Diagram Legend:

F_1	Anti-Pumping Relay
b11-b14	Breaker Auxiliary Switches
b21-b22	Limit switches for motor operating mechanism
b3, b4	Limit switches for isolated positions and service
b5	Interlocking contacts
M1	Motor for spring mechanism operation
N	Closing solenoid
O_1, O_2	Trip solenoid
a	Plug
d	Socket
W	Terminals
b6 I b6 II b6 III	Auxiliary switches indicating truck position
R_2	Series Resistance

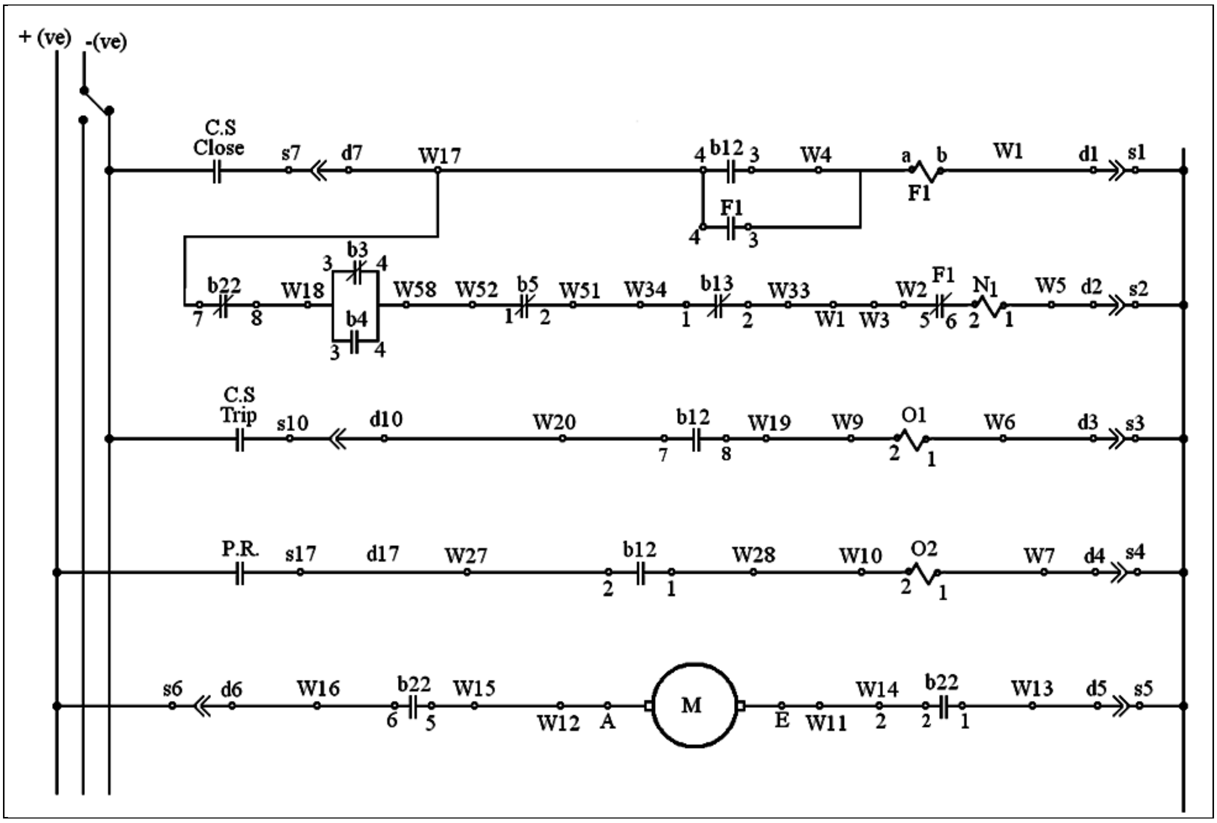


Fig. 2.3-11 Schematic Diagram for 69KV MOCB Type TRI

a. Closing operation mode:

1. Circuit breaker should be open i.e. its Normally Closed (NC) contact (b_{13}/1-2) of breaker auxiliary switch should be closed.

2. The closing spring should be fully charged i.e. the Normally Open (NO) contact (b_{22}/7-8) of limit switches should be closed.

3. The circuit breaker should be either in the service position i.e. its position limit switch b3 NO contact (b_3/3-4) should be closed.
   Or in the isolated position, i.e. its position limit switch b4 NO contact (b_4/3-4) should be closed.

4. The manual handle for Rack-in or Rack-out limit switch b5 NC contact (b_5/1-2) should be closed i.e. **the manual handle is not in place**.

5. The anti-pumping relay F_1 should be de-energized i.e. its NC contact (f_1/5-6) should be closed.

To close the circuit breaker locally you have to perform the following steps:

1. Set the mode selector switch to the local position.

2. Set the CB control switch (CS) in the closed position, so that the closing coil (N) is energized to close the circuit breaker and NO contacts of breaker auxiliary switches will close. When NO contact (b_{12}/3-4) closes and the control switch remains in the closed position, the anti-pump relay (F_1) will energize and close its NO contact (f_1/3-4) for self holding and open its NC contact (f_1/5-6) to prevent pumping of the circuit breaker, if the breaker trips while the closing control switch sticks in the closed position for any reason. Also at the same time of closing, the NO contacts of the spring charging motor (b_{22}/1-2) and (b_{22}/5-6) will close energizing the motor to recharge the spring to be ready for the next closing operation.

b. Opening Operation Mode

The circuit breaker should be in the closing position i.e. its auxiliary switch NO contact (b_{12}/7-8) should be closed, mode selector switch should be in local position, and the Control Switch (CS) in the trip position. This will energize the tripping coil (O1) and open the circuit breaker.

CONTROL CIRCUIT OPERATION OF CB (I.T.E.)

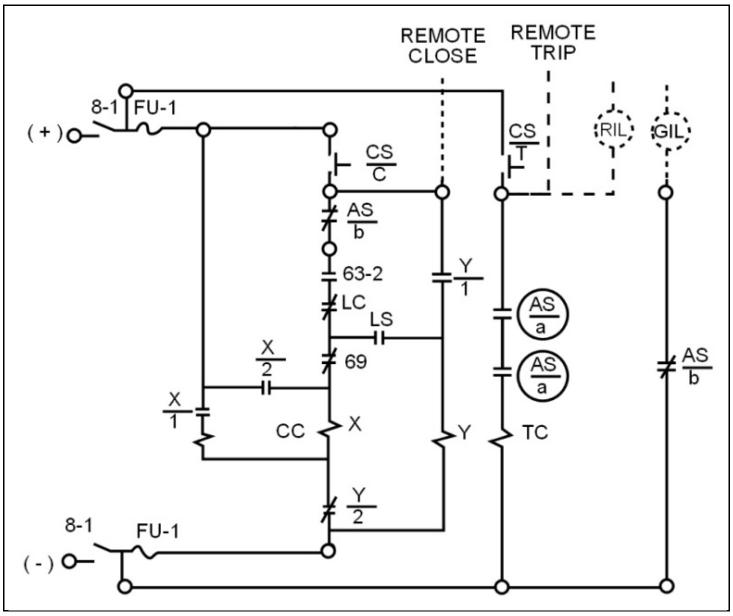


Fig. 2.3-13 Typical CB Control Circuit

Designation	Description
8-1	Control power switch
63-2	Lockout pressure switch
69	Permissive control switch
a or b	Auxiliary switch
a or b	Adjustable auxiliary switch
AS	Auxiliary switch assembly
CC	Closing coil
CS	Control switch
FU	Fuse
GIL	Green indicating light
LC	Latch checking switch
LS	Limit switch
RIL	Red indicating light
TC	Trip coil
X	Closing relay
Y	Anti-pump relay

CLOSING

The following steps required to close the breaker electrically:

1. Assuming standard control voltage is available at the ± terminals, power switch (8-1) closed, and fuses (FU1) are normal to power up the control circuit.
2. Device No. 69 Permissive Control Switch contact is in closed position (Manual Trip Device is not in mechanical lockout position).
3. Lockout Pressure Relay 63-2 contact is in closed position (sufficient air pressure is available to the control valve) and air supply valve is fully open.
4. Latch Checking Switch (LC) contact is closed.
5. AS/b contact is closed.
6. X Relay, Y Relay, closing coil, and all other associated electrical and mechanical equipment operable.
7. Operating mechanism and breaker are mechanically operable.

The breaker may be closed with control switch CS/C. A description of the operation of the closing circuit is as follows:

1. The X relay is energized closing contacts X/1 and X/2.
2. The air valve coil CC energizes through contact X/1 insuring complete operation of the air valve, even if the CS/C contact opens after a momentary closure. X/2 is for self holding X relay.
3. When the breaker approaches the fully closed position, the limit switch LS closes, energizing the Y relay, closing Y/1 contact and opening Y/2 contact.
4. When Y/2 opens, the X relay de-energizes, opening contacts X/1 and X/2.

5. Opening contact X/1 de-energizes the air valve coil (CC) shutting off the air. The breaker moves to the end of its stroke and is latched closed.

6. Opening contact X/2 removes the seal-in condition of the X relay.

7. In case the control switch CS/C is held in the closed position or remains closed, the Y relay stays energized through seal-in contact Y/1 while contact Y/2 is open. With contact Y/2 open, the X relay and Closing Coil (CC) of control valve cannot be energized and thus the breaker cannot pump.

TRIPPING

Tripping is accomplished by energizing the trip solenoid, which in turn, releases the trip lever. The lever and roller are now free to move due to the force of the breaker opening springs. The breaker is then free to open at full speed.

TRIP FREE OPERATION

When the breaker is tripped electrically, the trip-free mechanism disconnects the closing force from the breaker linkage, even if the piston rod is still held in the raised position by air pressure against the piston, or by the closing device for maintenance. Should the breaker close against a fault, the breaker can be tripped even when the closing circuit is still energized.

SUMMARY

- Circuit breaker has two control circuits; close circuit and trip circuit.
- The trip circuit receives trip signal manually or automatically (from protection).
- The control circuit includes auxiliary contacts, limit switches, auxiliary relays, and operating coil.

- The closing control circuit always has limitations to the close operation rather than the trip control circuit.
- Most of control circuit drawings, describe trip position for the CB.
- The control circuit has two-pole selector switch to select either of the two modes of operation - manual or by Protection.
- Anti pumping (52Y) is an interlock to prevent closing more than once.
- (52/a) contact is an auxiliary switch on the CB mechanism to open when CB has tripped.
- (52/b) contact is an auxiliary switch on the CB mechanism to open when CB has closed.
- Both of (52/a) and (52/b) are in the dc control circuit to perform the closing or tripping functions.
- Trip-free is an interlocking feature to prevent closing CB while trip is not finished, completely.

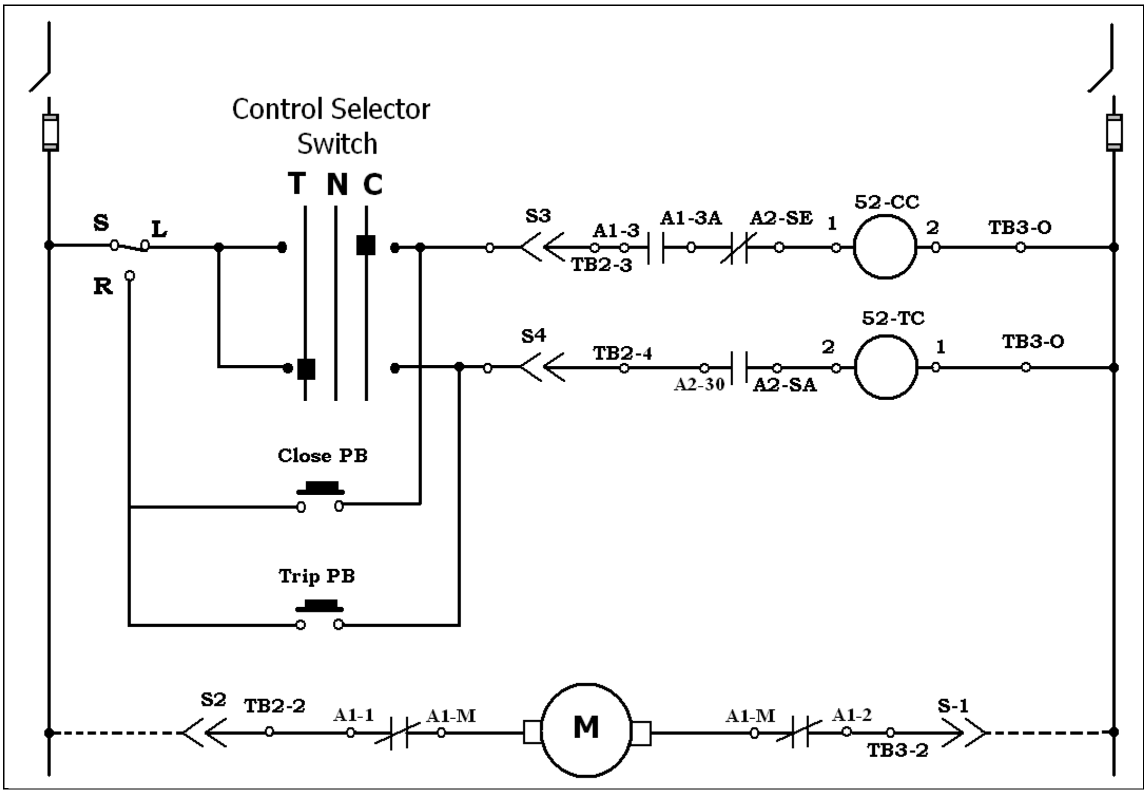
GLOSSARY

Anti-pumping:	Preventing repeated close operation
Interlock:	Preventing one or the other operation
Protection signal:	Signal that come from protective relays
Trip free:	Prevent close while trip operation not yet finished

REVIEW EXERCISE

Circle the letter (a, b, c or d) that correctly completes each statement or answers the question.

Study the control circuit for (S & S) circuit breaker shown below, and answer questions 1 to 4.



1. Locate limit switch contacts and explain their functions.

2. To close the breaker locally, turn the _____________ to _____________ position and the _____________ in _____________ position.
3. The mechanical manual trip is performed through _______________ and electrical manual trip by control switch in position trip, then the _______________ coil will be energized in case of contacts _______________ in the auxiliary switch is closed.
4. What is the meaning of:

a. 52-CC

____

b. 52-TC

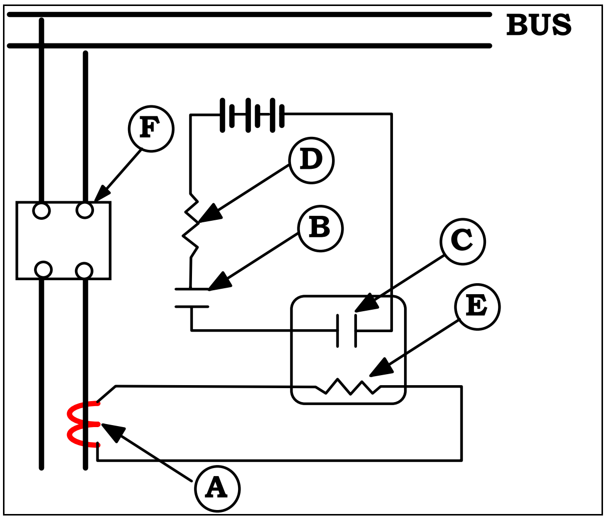
____

Complete the following:

5. The tripping mechanisms in the air blast circuit breakers are ____________.

6. The auxiliary switch will be adjusted to close as ___________ as possible in the closing stroke of the circuit breaker.

7. In the figure shown below write names of the parts pointed by the letters A, B, C, D, E and F.



A	
B	
C	
D	
E	
F	

Study the circuit breaker control circuit shown in the following diagrams, then answer questions 8 to 11.

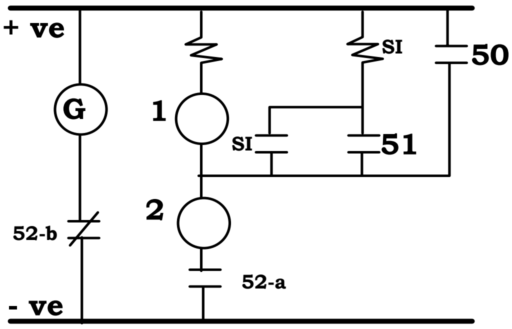


Diagram-1

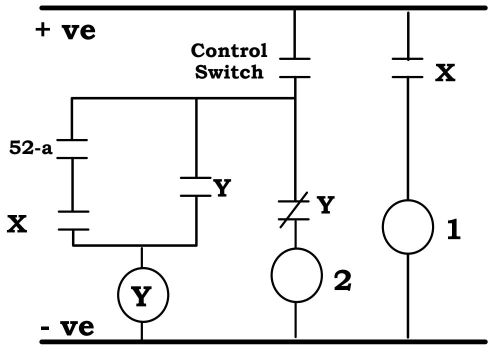


Diagram-2

8. Diagram ______ represents CB Closing Schematic Diagrams.

9. Diagram ______ represents CB Tripping Schematic Diagrams.

10. What are the parts represented by **number-1** and **number-2** in diagram-1?

____

____

____

11. What are the parts represented by **number-1** and **number-2** in diagram-2?

____

____

____

12. Protective relay contacts are usually capable to perform interrupting the tripping circuit high current. (**True / False**)

13. What is the function of anti pumping relay?

____

____

____

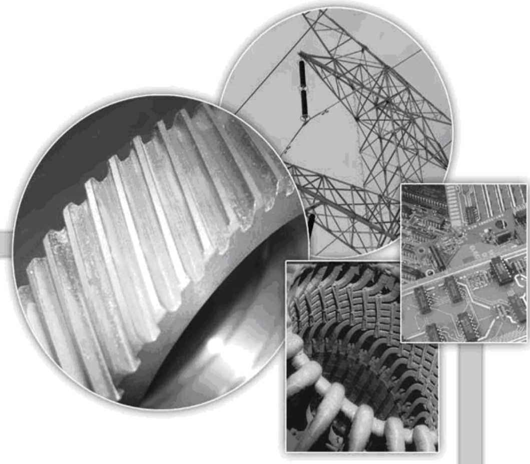
____

14. ___________________ is needed to open the trip circuit when the circuit breaker opens.

a. Cut-off anti pumping relay.
b. b-contact Auxiliary Switch.
c. a-contact Auxiliary Switch
d. Closing relay.

15. As long as the control switch is held in the closing position ___________________ stays energized and prevents another close.

a. closing coil.
b. Anti pumping relay.
c. overcurrent relay.
d. Under voltage relay.



LESSON 2.4

DISCONNECTING & EARTH SWITCHES

LESSON 2.4
DISCONNECTING & EARTH SWITCHES

OVERVIEW

This lesson familiarizes the trainees with disconnecting switches load break switches, and earthing switches. And their functions in power system.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Classify the different types of switches.
- Illustrate conditions for closing and opening of disconnecting switches.
- Verify the use of earthing switches.
- Demonstrate conditions of using switches for indoor and outdoor applications.

INTRODUCTION

Disconnect switches are used to isolate or connect equipment without load, to manage network configurations, to shift loads across the network and to complete shutdown of the system for maintenance.

There are two differences between disconnect switches and circuit breakers. The disconnect switches have no fighting chambers, relatively slow, and are not capable to open or close with load or when fault occurrence, while circuit breakers have the capability to do so because they are fast and equipped with arc interrupter. Disconnect switches can be operated manually only either locally or by remote signal from a control room.

They can break the connection between power source and electrical equipment with or without voltage, but without load current.

Some disconnect switches, designed to trip loads, are called **load break switches, or air break switches**. They have the fast operating characteristics to pass or interrupt loads in the presence of fighting chambers. They are employed as safety devices to de-energize circuits for safety during maintenance.

CLASSIFICATION OF SWITCHES

Switches may be classified in several different ways:

1. **According to Number of Poles**
    - Single
    - Double
    - Triple
2. **According to Type of Contact**
    - Knife blade
    - Butt contact

3. According to Number of Breaks

- Single break
- Double break

4. According to Method of Operation

- Manual force
- Motor or solenoid

5. According to Type of Services

- Power switches
- Disconnects
- Earth switches

Disconnecting switches are essential elements of electrical power transmission and distribution systems. They provide positive, visible air gap isolation of equipment and line sections for safe examination, maintenance and repair. In the closed position, Air Switches must provide adequate capacity to handle all normal and abnormal currents, flowing in the system. Finally, disconnecting switches must provide ease of mechanical or electrical operation even under adverse conditions such as heavy ice coatings or corrosive atmospheres.

In order to maintain the integrity of an electric power system, careful attention must be given to the selection and application of switches, as follows:

- Insulation level to be provided
- Continuous and momentary currents to be handled.
- Insulator characteristics required
- Enough electrical clearances and space limitations
- Current interrupting requirements, if they are load break switches.

Disconnect Switches are built in a variety of physical forms to accommodate the various requirements of electrical clearances and space limitations. When used as interrupter switches, various interrupting attachments are available.

Fig. 2.4-1 Single-Side Vertical Disconnect Switches

Disconnect switches are used primarily for isolation of equipment such as buses or other live apparatus. They are used for sectionalizing electric circuits such as buses or branch circuits. Disconnects are not used to break load current.

HORIZONTAL BREAK DISCONNECTING SWITCHES

As shown in Fig. 2.4-2 & 3 disconnects may be single break or double break.

Fig. 2.4-2 Horizontal Break Disconnect Switches

Fig. 2.4-3 Horizontal Double Break HV Disconnect Switches

VERTICAL BREAK DISCONNECTING SWITCHES

Vertical break disconnect switches shown in Fig. 2.4-4 have vertical motion for the moving contacts where the disconnect blades rotate with support insulators. Blades and insulators are directly coupled cause the blades to travel through 90° while the insulators revolve through 90°.

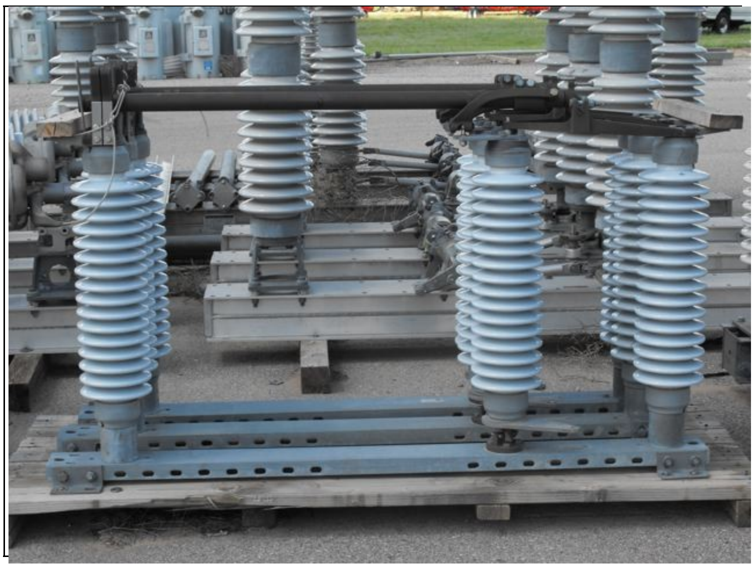


Fig. 2.4-4 Vertical Break Disconnect Switches

The three-phase disconnects may be ganged together to be operated on one rack as shown in Fig. 2.4-5.

Fig. 2.4-5 Gang Operation of Rack Mounted Disconnect Switches

INDOOR DOUBLE BREAK DISCONNECTING SWITCHES

Indoor double break disconnects, as shown in Fig. 2.4-6, are used to isolate the bus bars and or branch circuits. They are center-rotating type. The isolator may be driven by a motor or by hand in the event of motor failure or loss of power supply. The mechanism is fitted with 8-pole auxiliary switch for electrical interlocking of the isolator to prevent dangerous improper operations. The rotating arms of the isolator are made of copper or aluminum, with the contact parts of copper with hard silver surface.

Fig. 2.4-7 Double Break Disconnect Switches

The line isolator is similar as described above, but with the addition of integral earth switches. Both isolators are operated by an operating mechanism mounted to the cell fronts. The hand drives are provided with electromagnetic bolt interlocks with ON/ OFF positions, 8-pole auxiliary switches, and pad locking facilities.

LOAD BREAK SWITCHES (AIR SWITCHES)

Load Break Switches are electric air switches in circuits with several hundred thousand volts, designed to carry large currents without overheating in the close-position. Load break switches have enough insulation to isolate the circuit in open position, and are equipped with arc interrupters to interrupt the load currents.

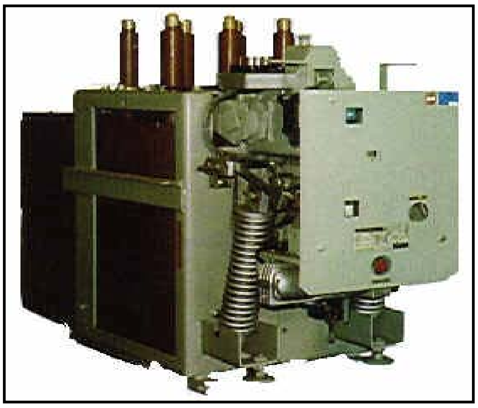


Fig. 2.4-8 Air Break Switch

EARTHING SWITCH

Earthing Switch is necessary to earth the conducting parts before maintenance, and to provide temporary short current pass while testing. There are three types of earthing switches:

1- Manually operated earthing switches
2- High speed earthing Switches
3- Protective earthing switches for neutral earthing

There are two applications for Earthing Switches:

- Maintenance Earthing Switches: These are single pole or three pole units; with manually operating mechanism or motor driven mechanism.
- High Speed Earthing Switches: These switches operate by spring energy, which is charged by motor-mechanism.

The earth Switch is mounted directly on the metal part of the equipment. It has to satisfy various requirements for earthing isolated sections of switchgear for protection of personal during maintenance tasks. For Earthing higher capacitances (cables, overhead line etc.) high speed Earthing Switches are employed, depending on the substation scheme, where the Bus Bars may be earthed either for maintenance or to replace some equipment.

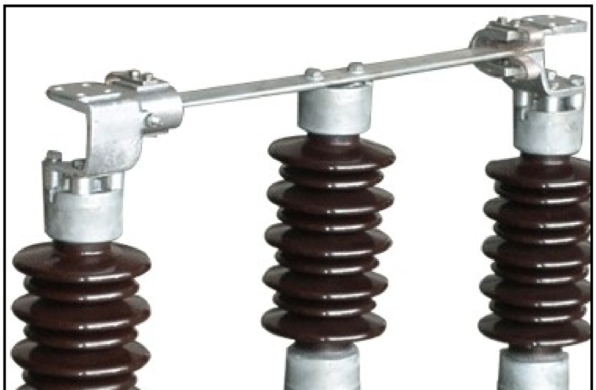


Fig. 2.4-9 Neutral Earthing Switch

GIS SWITCHES

Gas insulated switchgears are types of substations where circuit breakers, bus bars, switches, CTs and VTs are insulated with SF6 gas ducts. These disconnect switches are included with the system as shown in Fig. 2.4-10.

Fig. 2.4-10 GIS System including Disconnect Switches

SUMMARY

- Disconnecting switches are devices for isolating the circuits in the absence of loads.
- Disconnect switches can be operated locally or by remote signal.
- There are two types of disconnect switches:
  - Single break disconnect switch.
  - Double break disconnect switch.
- Load break switch is designed to break load current without any damage to the device.
- Load break switches are not capable to trip faults.

- Earthing switch is used to connect equipment to earth during maintenance for the safety of personnel.
- GIS disconnecting switches are used at substations where circuit breakers, bus bars, switches, CTs and VTs are insulated with SF6 gas ducts.

GLOSSARY

Air switch:	Type of switch that interrupts load current with air fighting chamber
Single break switch:	It has only one terminal to close and open
Double break switch:	It has two terminals to close and open
Load break switch:	Switch that can connect or isolate loads
GIS:	Gas insulated switchgear

REVIEW EXERCISE

Circle the letter a, b, c or d that correctly completes the statement.

1. The __________ is an air switch used when there is no current flowing in the circuit.
   a. Load break switch
   b. disconnect switch
   c. circuit breaker
   d. GIS switch

2. __________ means extinguishing or putting out arc in power switching applications.
   a. polarizing
   b. quenching
   c. firing
   d. tripping

3. A/An __________ is a visible flash or discharge of electricity across an air gap in an electrical circuit.
   a. induced current
   b. arc
   c. spark
   d. fire

4. Disconnect switches can trip faults.
   a. True
   b. False

5. Earth switches are to be closed after finishing the maintenance.
   c. True
   d. False

6. Disconnect switches can be operated after the main circuit breaker contacts are __________.
   a. opened
   b. closed
   c. energized
   d. installed

7. The switch shown is __________ switch.
   a. Horizontal disconnect
   b. Vertical disconnect
   c. Double break disconnect
   d. all of above

8. The device shown is __________ switch with earthing switch.
   a. Vertical disconnect
   b. Single break disconnect
   c. Double break disconnect
   d. all of above

9. The disconnect switches can be operated automatically by protection like circuit breakers.
   a. True
   b. False

Fill-in the blanks:

10. A typical disconnect switch is used to ________ equipment or lines for maintenance or repair.

11. List the three types of switches, classified according to the type of services.
   A. ________________
   B. ________________
   C. ________________

12. The purpose of the Air Switch is to provide positive, visible air gap isolation of equipment and line sections for safe ___________________________________

____

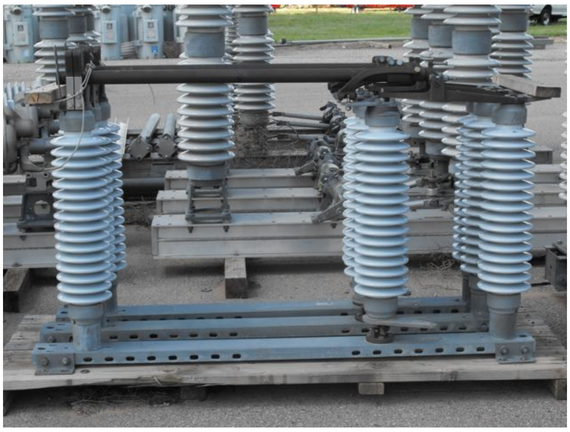
____

13. Earthing switch is used for:

____

____

14. Identify the types of disconnect switches in the following diagrams:



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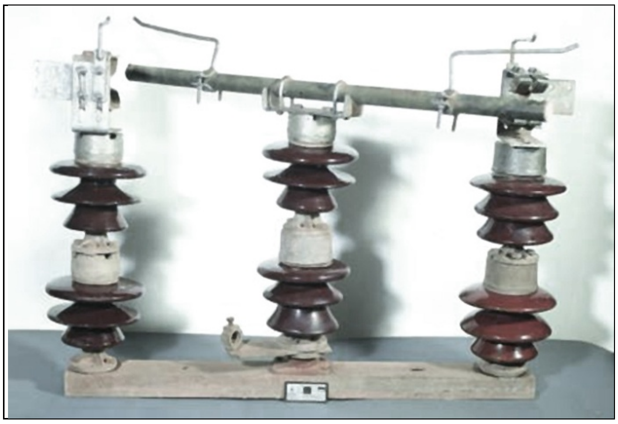

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TASK 2.4-1

OUTDOOR DISCONNECTING AND EARTH SWITCHES

OBJECTIVE

Upon completion of this task, the participants will be able to:

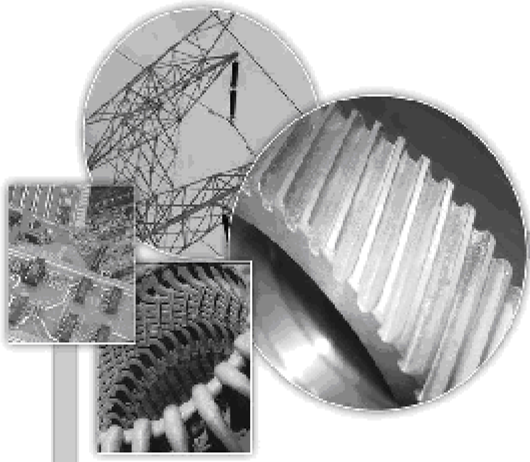
- Identify the different types of switches.

TOOLS, EQUIPMENT & MATERIALS

- Some disconnecting and earthing switches

PROCEDURE:

1. Identify two general types of Air Switches (outdoor type).
2. Explain the primary use of earth switch.
3. Explain the primary use of disconnect switch.
4. Illustrate the single break and double break switches.
5. Identify the parts of disconnect switch.
6. Identify the movement of moving contact, vertical or horizontal.
7. Explain the difference between disconnect switch and earth switch.
8. Identify the single phase or three phase switches.



UNIT 3

POWER SYSTEM EQUIPMENT

UNIT-3
POWER SYSTEM EQUIPMENT

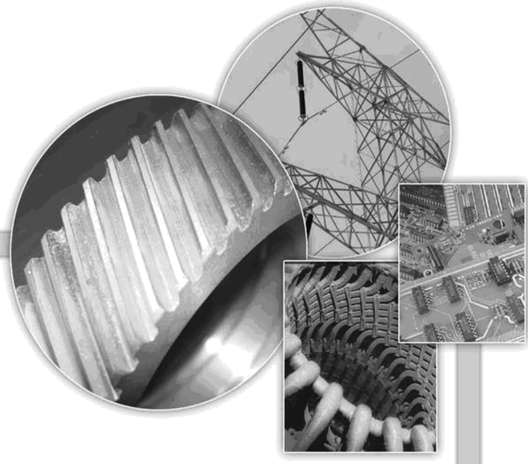
OVERVIEW

In this unit, the trainees learn the importance of power generation, insulators, bus bars, grounding systems, power supplies, and battery chargers as the main equipment of power system. The unit describes the reactive power effects and the applications of using regulated power supplies. Furthermore, the unit explains the elements and components of protective system.

OBJECTIVES

Upon completion of this unit, the trainees will be able to:

- Identify the power system generator.
- Demonstrate the importance of reactive power compensation.
- Illustrate the functions of bus bars, insulators, switches.
- Verify the importance of power system grounding.
- Demonstrate the applications of regulated power supply and battery chargers.



LESSON 3.1

POWER SYSTEM GENERATOR

LESSON 3.1
POWER SYSTEM GENERATOR

OVERVIEW

This lesson discusses three-phase generator used in power system describing principles of operation, types of synchronous generators, generator excitation, excitation effect in power factor correction and synchronizing.

OBJECTIVES

Upon completion of this lesson, the trainees should be able to:

- Describe the principle of operation of an AC Generator.
- Identify parts and types of AC generators.
- Describe the excitation effect in power factor improvement.
- Demonstrate the paralleling operation and synchronizing of generators.

Task 3.1-1: Synchronizing operation of parallel generators

PRINCIPLE OF OPERATION FOR GENERATOR

The fundamental of operation is based on intersecting rotating magnetic field to fixed conductor, or vice versa, result in generating electromagnetic force (EMF) in the conductor in both cases.

In fact, there are a large number of conductors divided into three groups, 120^o apart for each other forming armature. Winding produces three phase voltages at the three terminals as shown in Fig. 3.1-1.

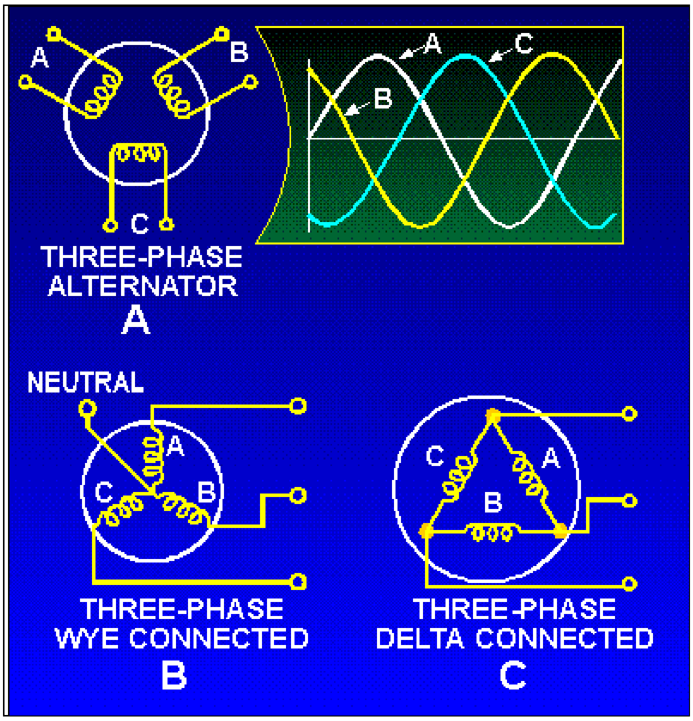


Fig. 3.1-1 Generating Three Phase Voltage

A complete cycle is generated in any conductor on the armature when a pair of poles has cut across it. Hence, to find the frequency of the generator, it is only necessary to calculate the number of pairs of poles passing any stator conductor in one second. A four-pole rotor would have two pairs of poles and would induce two cycles per revolution. Therefore, when traveling at a speed of 1800 RPM (30 RPS), would induce a 60 Hz voltage in the stator conductor. A two-pole rotor would have one pair of poles and would induce one cycle per revolution. Therefore, when travelling at a speed of 3600 RPM (60 RPS), would also induce a 60 Hz voltage in the stator

conductors. These alternators could be operated in parallel even though they are rotating at different speeds, 1800 RPM and 3600 RPM, because they are both producing a 60 Hz voltage. In order that the frequency remains constant, the speed of each generator rotor must be constant; therefore, the prime mover must be able to maintain a constant speed under varying load.

The stator of a three-phase generator is made up of three windings, placed 120 electrical degrees apart. The stator when cut by the field of the rotor, induces a three-phase voltage in the stator.

CLASSIFICATION OF GENERATORS

CLASSIFICATION ACCORDING TO REVOLVING WINDING

Generators are manufactured in two principal types:

1- REVOLVING ARMATURE WINDING TYPE
2- REVOLVING FIELD WINDING TYPE

REVOLVING-ARMATURE GENERATOR

Generator has two parts stator as fixed part, and rotor as revolving part. In order to produce voltage, DC excitation supply is connected to the excitation circuit. Three-phase output voltage is produced in armature circuit. If the armature circuit is mounted on the revolving part, and the excitation circuit is on the stator (stationary field poles), three slip rings are needed for the output voltage as shown in Fig. 3.1-2. The revolving-armature generator is commonly used for low power generation system.

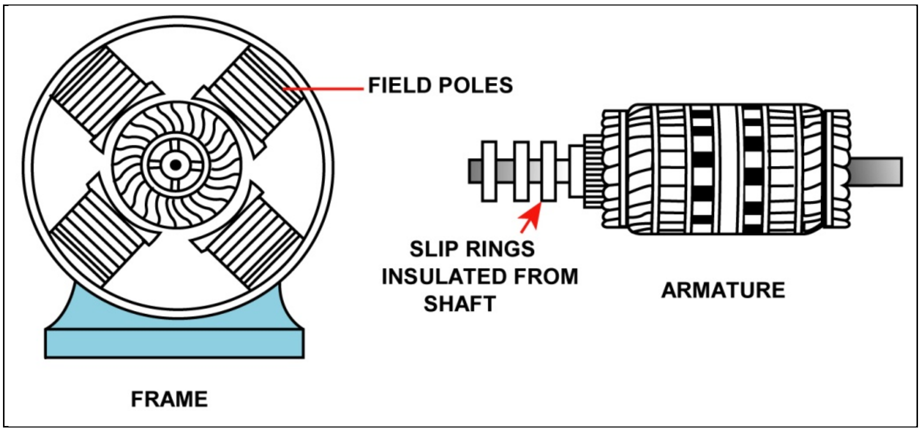


Fig. 3.1-2 Parts of Revolving-Armature Type Generator

REVOLVING-FIELD GENERATOR

In this type, the armature circuit is mounted on the stator and excitation circuit in the revolving part that is fed from rotary rectifier that revolves with the rotating system, as shown in Fig. 3.1-3. The revolving-field generator is commonly used for large power generation system.

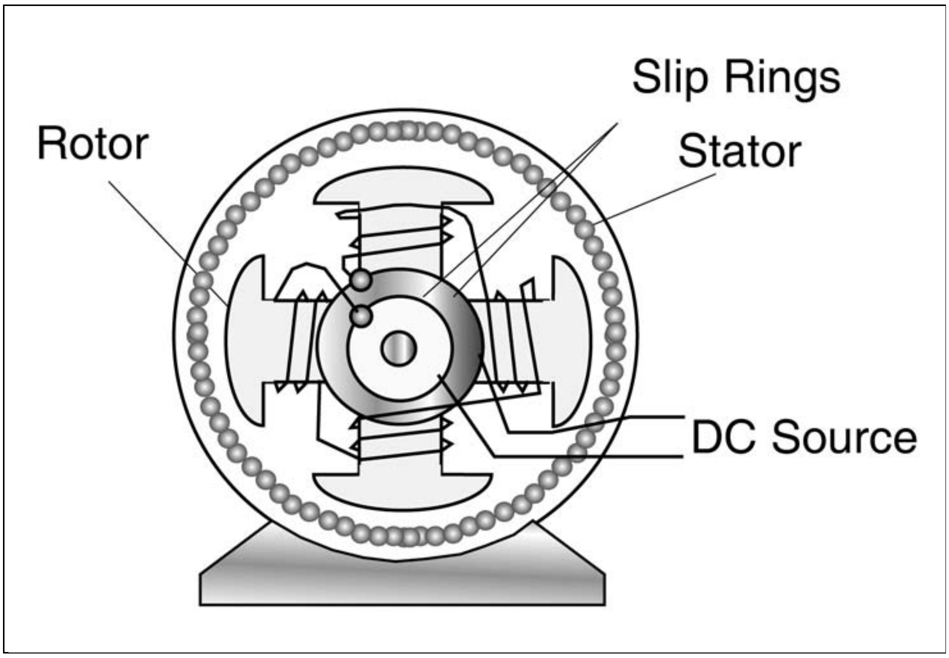


Fig. 3.1-3 Revolving-Field Type Generator

CLASSIFICATION ACCORDING TO STATION TYPE

There are two types of generators according to revolving speed:

1- SALIENT FIELD GENERATOR

2- NON-SALIENT FIELD GENERATOR

SALIENT FIELD GENERATOR

This type of generator is used for low speed application, like hydro power plant (Fig. 3.1-4). The field excitation has large number of poles to overcome low speed.

Fig. 3.1-4 Salient Field Generator Rotor

Equation (1) indicates the relation between speed generator speed and number of pole pairs.

$$\mathbf{f = P \times N / 60}$$

Where: f = Frequency in Hz (Cycles/second)

P = Number of pole Pairs

N = Speed in rpm (revolutions per minute)

In order to keep frequency fixed at 60 Hertz, with low speed, the number of pole pairs, is chosen at the time of manufacture.

NON-SALIENT FIELD GENERATOR

This type of generator used for high-speed application, like steam or gas power plant as shown in Fig. 3.1-5. The excitation field winding has the minimum number of pole pairs (one-pole pairs).

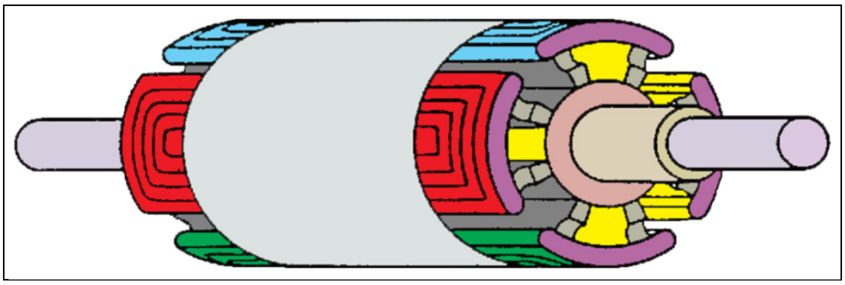


Fig. 3.1-5 Non-Salient Field Generator Rotor

EXAMPLE 1-1

An AC Generator in hydro power plant is running at 450 RPM for 60 Hz frequency. Determine the number of poles in the field circuit required.

SOLUTION

$f = P \times N / 60$

Then, $P = 60 \times 60 / 450 = 8$ pole pairs

Number of poles $= 2 \times 8 = 16$ poles

EXAMPLE 1-2

2-pole AC Generator in steam power plant is running at 60 Hz frequency. Determine the generator speed.

SOLUTION

Number of poles = 2, number of pole pairs = 1

N = 60 x f / P

Then, N = 60 x 60 /1 = 3600 r.p.m.

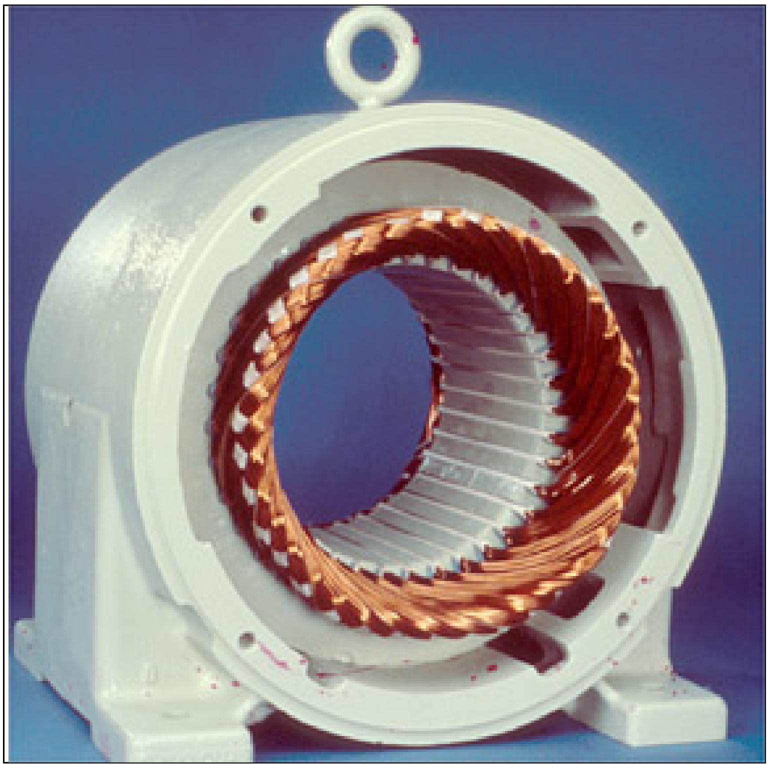


Fig. 3.1-6 Stator Winding

GENERATOR VOLTAGE CONTROL

Generator output voltage depends on the rotor speed and field strength (excitation current). Because the number of conductors is determined in the design phase and cannot be changed, and since the speed must remain constant, the only control over the voltage would be by varying the excitation current.

When an Alternator is driven at a constant speed, the frequency would be held constant and the voltage would be regulated by means of the DC field strength. The field excitation circuit is controlled either manually by a rheostat connected in series

with the DC excitation supply as shown in Fig. 3.1-7, or automatically by programmable control system.

The induced output voltage is generated according to the following equation:

$V = 4.44\ N\ \varphi\ f$

Where: N: number of coils

f: frequency

φ: excitation flux

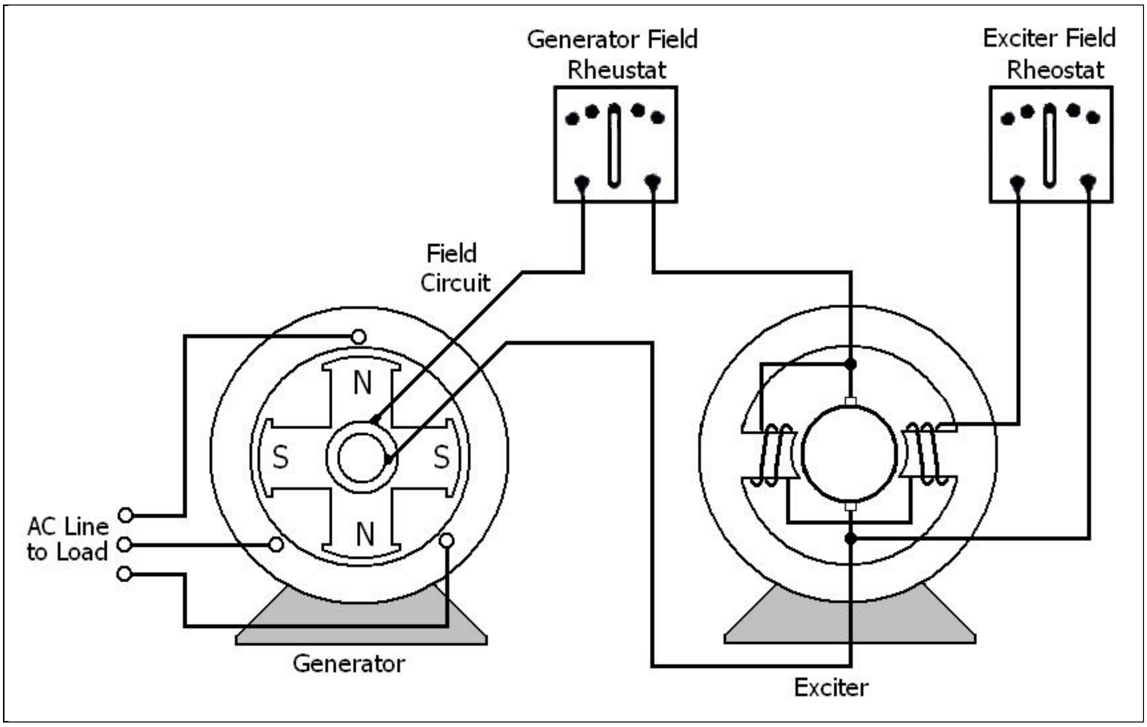


Fig. 3.1-7 Generator Voltage Control

OPERATION OF MULTIPLE GENERATORS IN PARALLEL

When considering the excitation and mechanical input power in generator operation and there rules of changing voltage and/or MVAR and changing frequency and/or MW respectively-the following cases must be considered:

a) The generator is running without load before synchronizing (single)
b) The generator is loaded but not connected to any other generator (isolated)
c) The generator is synchronized to a bulky unified network (integrated)

CASE a:

- Changing excitation changes the generated and terminal voltages
- Changing the input power from the prime mover changes the generator speed (frequency).

CASE b:

- If the excitation is controlled automatically the automatic voltage regulator (AVR) changes the excitation to meet the changes in MVar needed by the load
- The governor will adjust the prime mover output power to the generator to supply the MW needed by the load.
- Controlling MVar and MW will keep the voltage at its rated value.
- If the excitation is changed manually with constant load, the generated and terminal voltage.
- If the input power to the generator is changed manually the speed an frequency changes.

CASE c:

- Mainly changing excitation changes reactive power (MVar) and changing input power (fuel or steam) changes active power (MW).

This is the major loop but there are minor loops:

- In power systems voltage is affected by load variation. By the nature these loads have two parts, active (resistive) and reactive (inductive). So heavy load changes tend to change the voltage and frequency to certain extent according to the load parts (resistive and active) but the control of all large generators especially large ones (key generator) face this tendency by changing MW & MVar to maintain the system voltage at its rated value. Every generator contributes (according to its capability) to maintain the voltage.

- The same happens with the frequency changes. MW changing is required to cover the resistive current needed by active load. MW adjusting is achieved by changing the fuel and amount of steam.
- Adjusting inductive current drawn by reactive load finally maintain the voltage level.

TYPES OF EXCITATION SYSTEM

A DC supply is required to energize the rotor field coils, as shown in Fig. 3.1-8. There are so many ways to generate this DC supply.

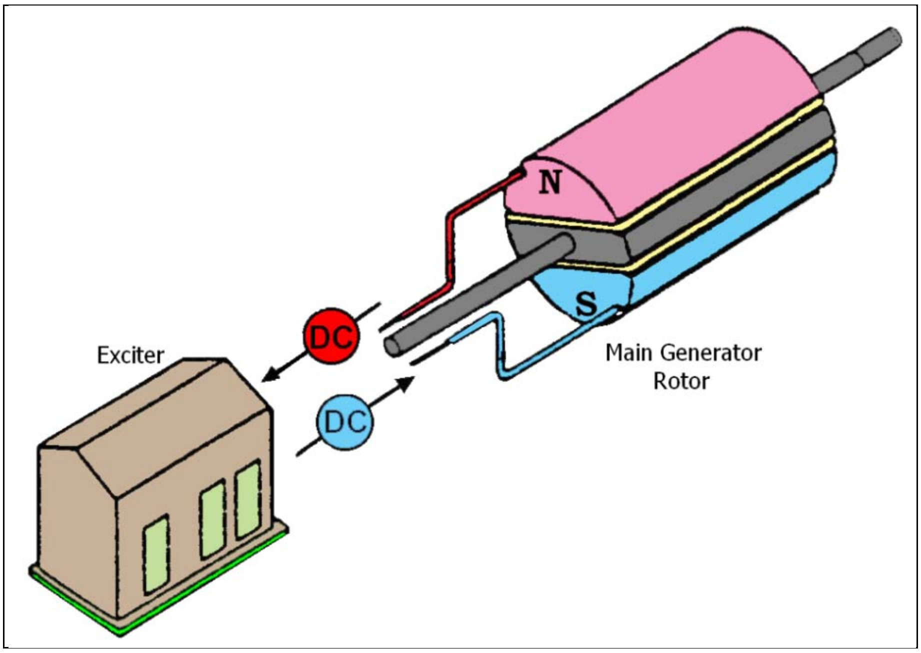


Fig. 3.1-8 DC Supplied to Main Generator's Rotor Field Winding

Excitation systems generally fall into two broad categories:

- System with brushes and slip rings exciter
- Systems with brushless exciter

BRUSHES AND SLIP RINGS EXCITER

This type of exciter is equipped into the revolving armature type generator, depending on stationary rectifier circuit. Compared to the other type, it gives low output power serving the temporary and small loads.

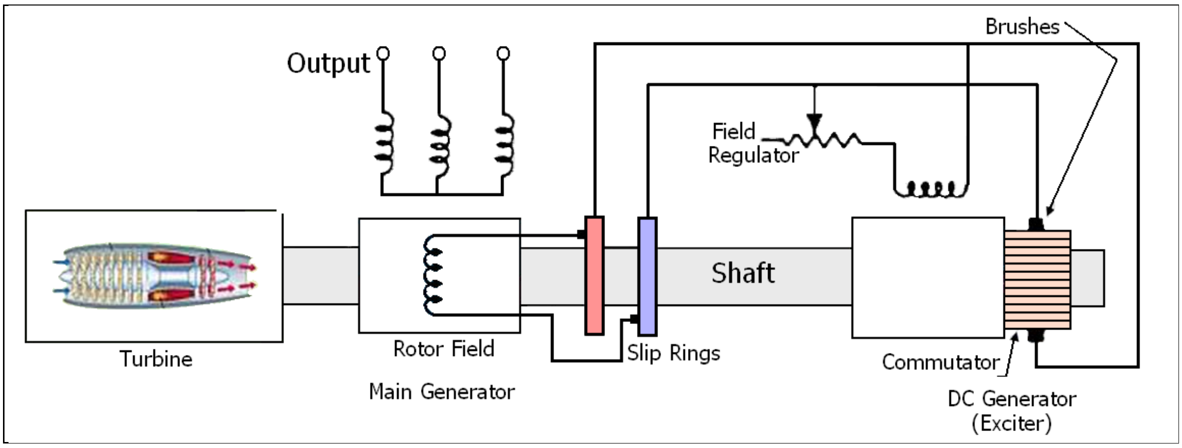


Fig. 3.1-9 Circuit Diagram of AC Generator with Self-Excited DC Generator

The AC electricity coming from the stationary armature passes through a rectifier. The rectifier is an electronic device that changes AC to DC. The DC then flows through the field windings on the main Generator through slip rings and brushes.

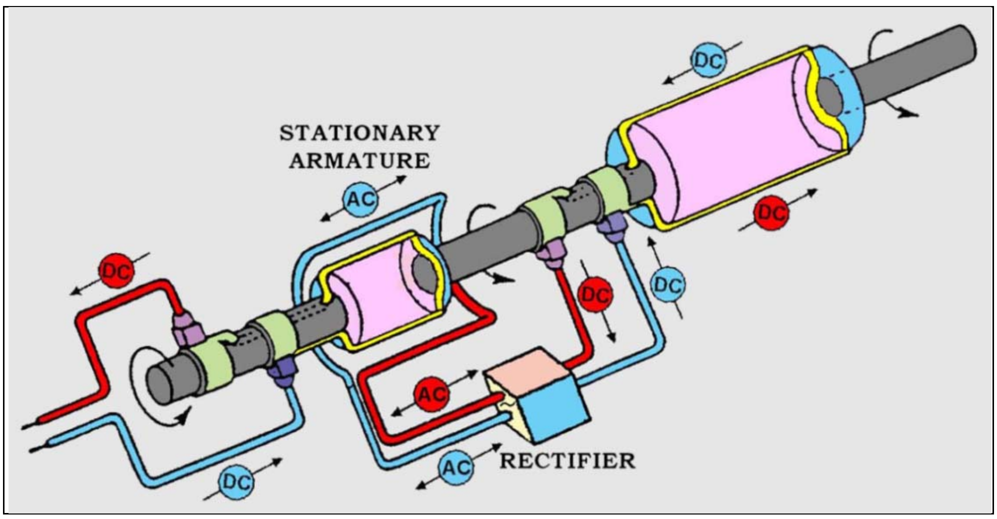


Fig. 3.1-10 Brush and Slip Ring Excitation

The voltage regulation in this type of exciter is also achieved by controlling the DC to the Exciter rotor field windings. Notice that this current is delivered through slip rings and brushes.

BRUSHLESS EXCITER

This type of exciter is equipped into the revolving field type generator, depending on rotary rectifier circuit and permanent magnet DC generator compared with the other type. It gives high output power for large power plants to serve sharing with the network to supply industrial loads.
The second type of excitation is called the brushless excitation system, as shown in Fig. 3.1-11. This method of excitation avoids the inherent inefficiencies of slip rings and brushes. The Exciter in the brushless excitation system consists of an AC Generator with a rotating armature and a stationary magnetic field. The AC electricity generated in the rotating armature is converted to DC by a rectifier mounted on the same shaft as the armature

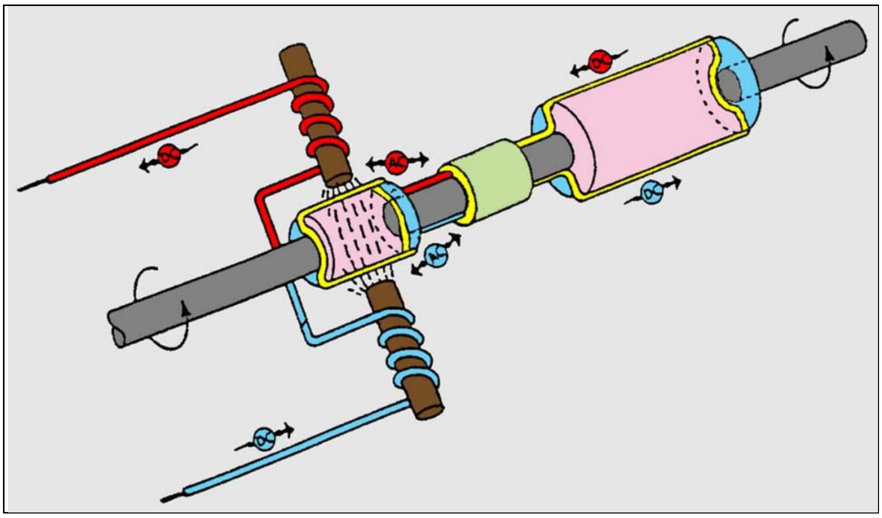


Fig. 3.1-11 Brushless Excitation

The fact that the Exciter armature, the rectifier and the main Generator field windings are all on the same rotating shaft, allows for a direct connection between the exciter's output loads and the field windings on the main Generator.

The brushless Exciter assembly also includes a pilot Exciter that supplies the current for the stationary field windings around the exciter, as shown in Fig. 3.1-12.

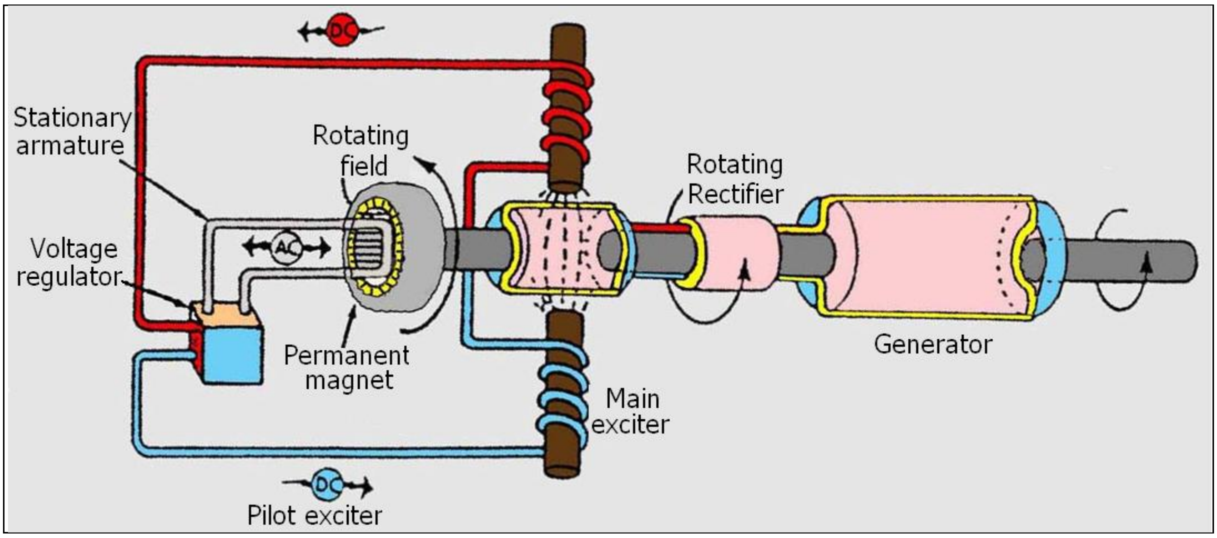


Fig. 3.1-12 Brushless Excitation System with Permanent Magnet Generator

The pilot Exciter is an AC Generator that consists of a permanent magnet rotating field located at the end of the Exciter rotor and a stationary armature. The pilot Exciter is usually referred to as the Permanent Magnet Generator **(PMG)**. Before it reaches the field windings on the main exciter, the output from the PMG is rectified and controlled by the voltage regulator.

BRUSHLESS EXCITER COMPONENTS

The basic functional components of the brushless Exciter are the Permanent Magnet Generator **(PMG)**, the voltage regulator, the AC Exciter Generator and the rotating rectifier.

One of the principal advantages of this system is that many of the major components, PMG, main Exciter armature windings, and rectifier wheel are mounted on the same shaft, as shown in Fig. 3.1-13.

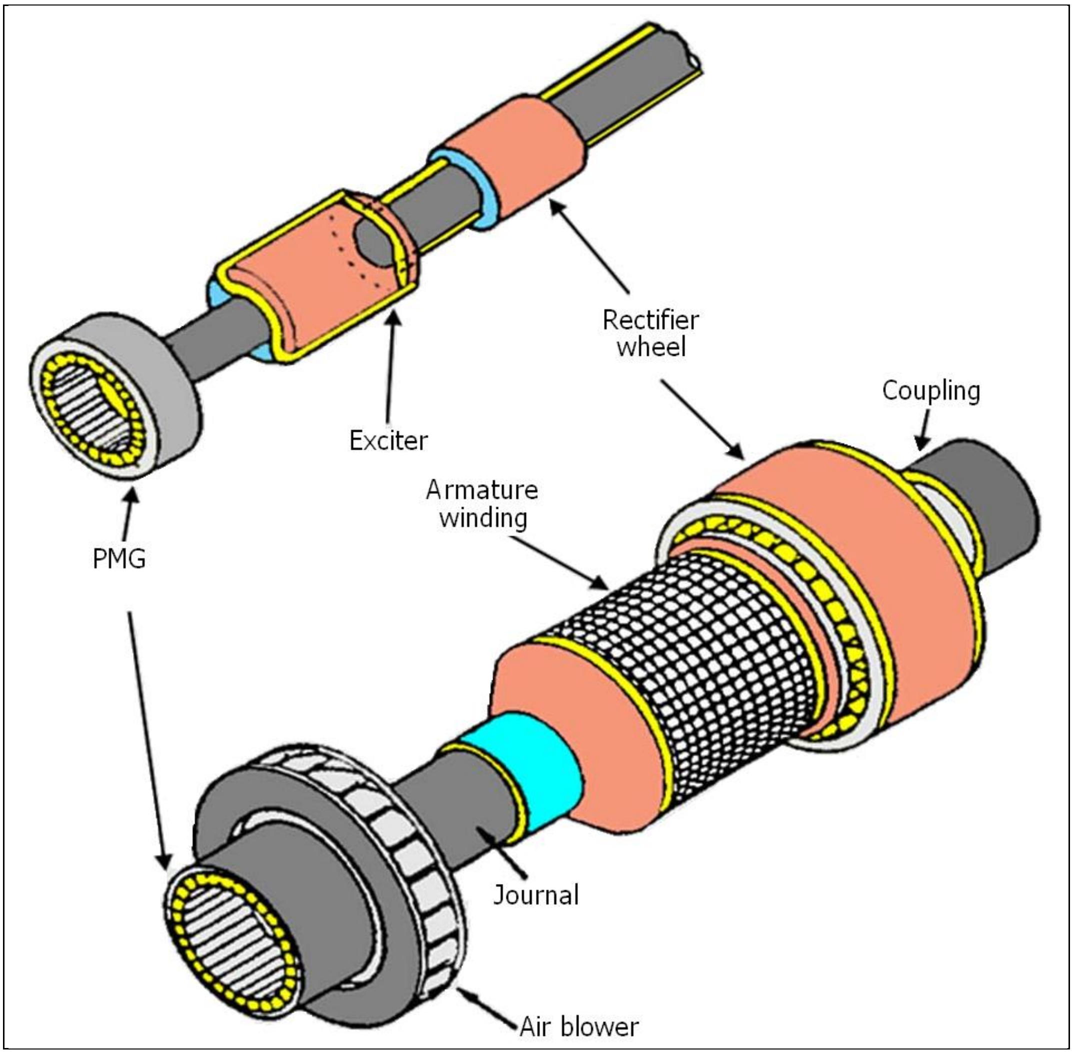


Fig. 3.1-13 Exciter Rotor Shaft

A Permanent Magnet Generator is used to generate the voltage for the field of the main Exciter in three-phase. This voltage is rectified through a rectifier rotating with the shaft and fed into the rotor of the Generator to energize the field, as shown in Fig. 3.1-14.

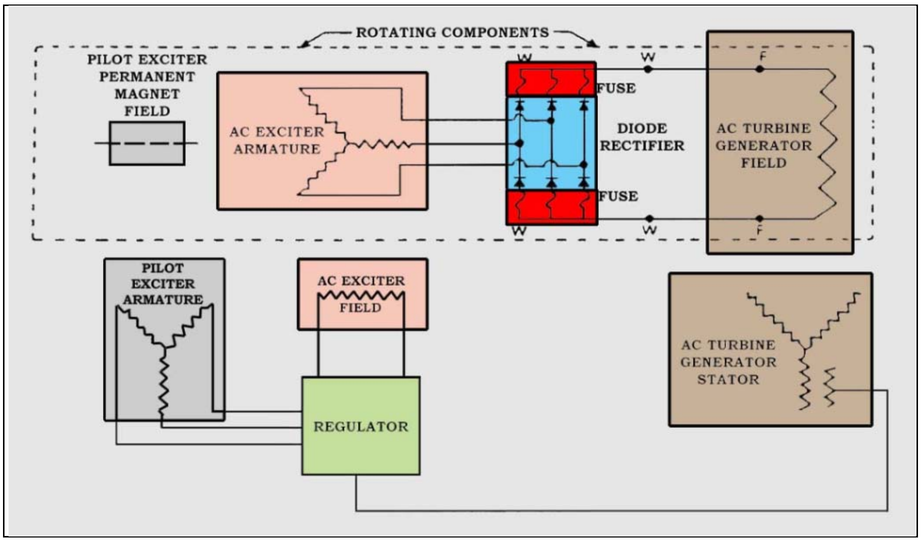


Fig. 3.1-14 Typical Rotating Rectifier Excitation System

GENERATOR COOLING

- Generator cooling is needed to remove the heat energy produced by the large currents flowing through the conductors. This includes the DC flowing through the rotor windings as well as the AC being induced in the stator coils. Another source of heat in the generator operation is the friction in the bearing.
- To remove this excess heat energy, hydrogen gas is circulated through the Generator by a blower attached to one end of the rotor, as shown in Fig. 3.1-15.
- Hydrogen is used as a cooling medium because of its excellent heat absorbing capabilities under pressure and because it is significantly lighter than air and requires much less energy to force it to flow through the Generator.
- Small Generators (usually below 30 Mega-Watts) are cooled by circulating air through the rotor and stator. As a small generator exciter is cooled with circulating air.
- Units that rated between 30 and 200 Mega-Watts are cooled by circulating hydrogen between the rotor and stator. This type of cooling is called **conventional hydrogen cooling**.

Fig. 3.1-15 Hydrogen Blower

- Units larger than 200 Mega-Watts are cooled by circulating hydrogen through hollow passages inside the stator coils. This is called **inner cooling**.
- In another design of inner cooled generator, hydrogen is circulated through the rotor and stator and water through hollow conductors in the stator coils. The hydrogen picks up the excess heat energy from the rotor and stator.

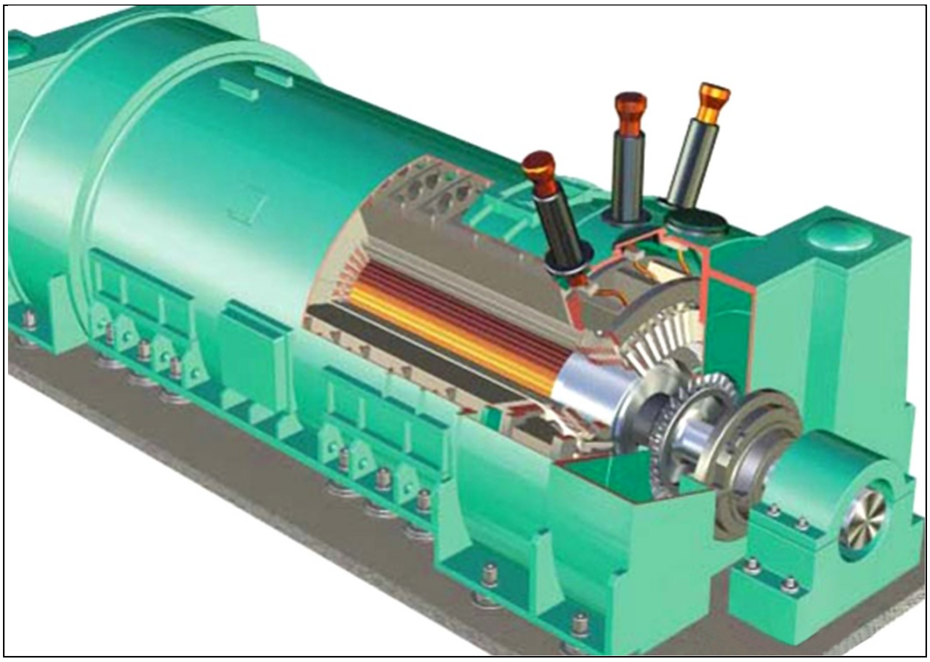


Fig. 3.1-16 Hydrogen Coolers

- The blower directs hydrogen through the coolers that are mounted in the Generator frame. As it passes over the water tubes in the coolers, the gas temperature is reduced. Once cooled, the gas is re-circulated between the stator and rotor, as shown in Fig. 3.1-16.

  WARNING

  It is important to maintain purity of hydrogen to reduce frictional losses as well as to avoid forming explosive mixtures with air.

SYNCHRONIZING AND PARALLEL OPERATION OF GENERATORS

In order to connect (synchronize) one generator to another or to the system, one of them is selected as the running, the other generator is the incoming.

Four conditions must be satisfied carefully for paralleling (synchronizing) as following:

1. Frequency must be the same

The incoming generator must match its frequency, by speed adjustment, with the main generator or system. The speed adjustment is accomplished by means of the prime mover. The incoming generator is adjusted to produce a slightly higher frequency than that of the system.

2. Phase sequence must be the same

The phase sequence of the generator is made to agree with the phase sequence of the system by interchanging any two of its three output terminals. This is done only once at the first synchronizing.

3. Voltages must be the same

The voltage of the second generator is controlled before paralleling by adjusting its excitation current until it is the same as the running or the system voltage.

4. Instantaneous phase angle at the moment of paralleling

Instantaneous phase position of the incoming generator must be the same at the instant of paralleling with the running generator of the system just before synchronizing; there may be a slight difference of frequency between the incoming generator and the main system. This slight difference in frequency, which is controlled by its rotor speed, causes the system to continually gain on the generator and periodically the two will be equal and in-phase. It is at this instant that they can be locked in. If the two, system and generator, were locked in at even a few degrees off the desired position, there would be an interchange of current that would cause a disturbance on the system, as shown in Fig. 3.1-17.

It must be noticed that there is a time in m seconds between the synchronizing signal and the CB actual closing so a few degrees off one desired position is required.

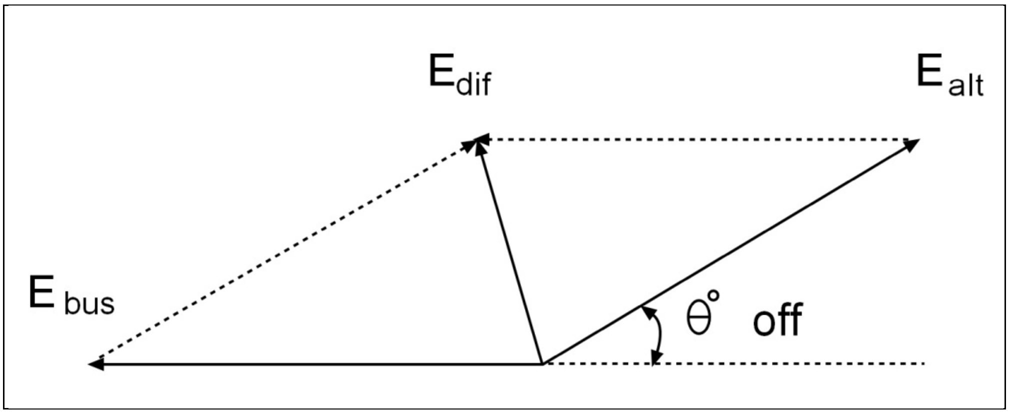


Fig. 3.1-17 Instantaneous Phase Positions

The proper phase relationship for parallel operation can be found by the use of an instrument called **Synchroscope** or by means of phase sequence lamps. Once the two systems are locked in, the DC field of the generator loses its ability to control voltage. It can now be used for power factor correction. A strong field creates a leading current while a weaker field creates a lagging current.

LOADING OF PARALLELED GENERATORS

The power fed to the load by one generator or a group of generators, operating in parallel, is controlled by the prime mover(s). As more energy is supplied by the prime mover, the rotor of the generator tries to move ahead of its former position. This slight movement changes the angle between the bus voltage (terminal voltage) and the generated voltage. This shift creates a greater voltage difference causing the alternators load current to increase. The counter torque created by this added load, keeps the generator traveling at the same speed as before.

SUMMARY

- A voltage is generated when a stationary magnetic flux intersects a rotating conductor or when a moving magnetic flux intersects a stationary conductor.
- A four-pole rotor has two pairs of poles and would induce two cycles per revolution.
- All types of synchronous generators must be supplied with field excitation currents from a DC source**.**
- The frequency of a Generator is a direct function of speed and the number of pole pairs in the field circuit.
- The three-phase output winding is called armature circuit.
- The rotary rectifier is mounted in the revolving field type generator.
- The output voltage for single generator (alternator) is controlled by the excitation circuit.
- Controlling the excitation current for multiple alternators lead to control the reactive power.
- Synchroscope is used to check synchronizing between alternator and system network.

FORMULAE

$$f = P \times N / 60$$

Where:

f = frequency in hertz (Cycles/second).

P = Number of pole pairs.

N = Speed in rpm (revolutions per minute).

$$V = 4.44\, N\, \varphi\, f$$

Where:

f: frequency

N: number of turns

φ: Field flux

GLOSSARY

Stator:	Stationary part of AC machine
Armature circuit:	Generator three phase output circuit
Rotary rectifier:	Bridge rectifier mounted on the rotor
Alternator:	AC generator
Pole pairs	Two poles
Slip rings:	Metal rings to make electrical contacts with revolving circuit through brushes
Excitation circuit:	DC circuit to supply the generator with field strength
Synchroscope:	An instrument used to check synchronizing

REVIEW EXERCISE

1. An Eight-pole rotor would have two pairs of poles and would induce two cycles per revolution.
   a) True   b) False

2. For a single operated generator, controlling excitation current leads to:
   a) Control output voltage.   b) Control reactive power.

3. Slow speed generator has:
   a) Salient field rotor.   b) Non-salient field rotor.

4. Fast speed generator has:
   a) Salient field rotor.   b) Non-salient field rotor.

5. An AC Generator has 8-poles is running at 1800 RPM. The output frequency of the Generator should be ………… Hz.
   a) 60 Hz.   b) 120 Hz.
   c) 30 Hz.   d) 45 Hz.

6. For multiple paralleled generators, controlling excitation current leads to:
   a) Control frequency.   b) Control reactive power.

7. Hydrogen is used in the generator for:
   a) Insulating.   b) Slowing the rotor speed.
   c) Cooling.   d) Protection of current leakage.

8. The output voltage of an AC Generator depends on:
   a) Operating frequency.   b) Field flux.
   c) Number of turns in excitation winding.   d) All of the above.

9. Large power can be generated by:
   a) Revolving armature generator.   b) Revolving field generator.

TASK 3.1-1
SYNCHRONIZING AND OPERATION OF PARALLEL GENERATORS

OBJECTIVES

Upon completion of this task, the participants will be able to:

- Demonstrate synchronizing and parallel-operation of generators.

TOOLS, EQUIPMENT & MATERIALS

- 2- motor-synchronous generator sets
- 1- Synchroscope
- 1- Multimeter
- 1- Phase sequence meter

PROCEDURE

Step 1: Energize the first motor-generator set.

Step 2: Carefully adjust excitation circuit to control output voltage.

Step 3: Carefully adjust the motor speed to control frequency.

Step 4: Carefully adjust both of the excitation and speed to set output voltage to 600V AC and frequency to 60 Hz.

Step 5: Start to energize the second motor-generator set.

Step 6: Repeat Steps 2, 3 & 4 with the second motor-generator set.

Step 7: Carefully check phase sequence, frequency, and voltage for each set verifying the required conditions until they are all the same.

Step 8: Use the synchroscope and carefully monitor its pointer until its motion become very slow in the fast direction.

Step 9: Carefully close the circuit breaker to tie the two sets.

Step 10: Load the sets with suitable load, monitor the voltage and frequency.

Fig. 1-1 Motor-Generator Set

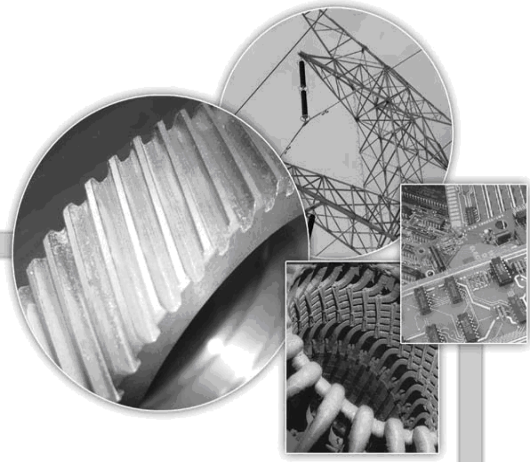
Step 11: You should recognize a drop in both voltage and frequency.

Step 12: Carefully readjust excitation and speed for any of the sets until the voltage reads 600V and frequency 60 Hz again.

Step 13: Open the circuit breaker between the two sets.

Step 14: Carefully decrease excitation and speed for each set until the machines stop moving.

Step 15: Shut down the supply voltage and housekeeping, as instructed.



LESSON 3.2

BUSES, INSULATORS & BUS BAR DESIGN

LESSON 3.2

BUSES, INSULATORS & BUS-BAR DESIGN

OVERVIEW

This lesson discusses Bus-Bar shapes, functions of bus ducts and how they are cooled, current carrying capacity, insulators, and their types, substation types and familiarization with Bus Bar design.

OBJECTIVES

Upon completion of this lesson, the trainees should be able to:

- Specify Bus-Bar shapes.
- Explain functions of bus ducts and how they are cooled.
- Familiarize with current carrying capacity.
- Familiarize with insulators and their types.
- Familiarize with substation types.
- Familiarize with Bus-Bar design.

INTRODUCTION

Bus Bar is a term used for main bar or conductor carrying an electric current to which many connections may be made to supply current to other sub-circuits. Buses are convenient means of connecting switches and other equipment in various arrangements. Buses are normally made of copper or aluminum. Both of these metals are good conductors of electricity. Buses may be in the shape of tubes, bars, or cable. Fig. 3.2-1 shows typical shape of buses.

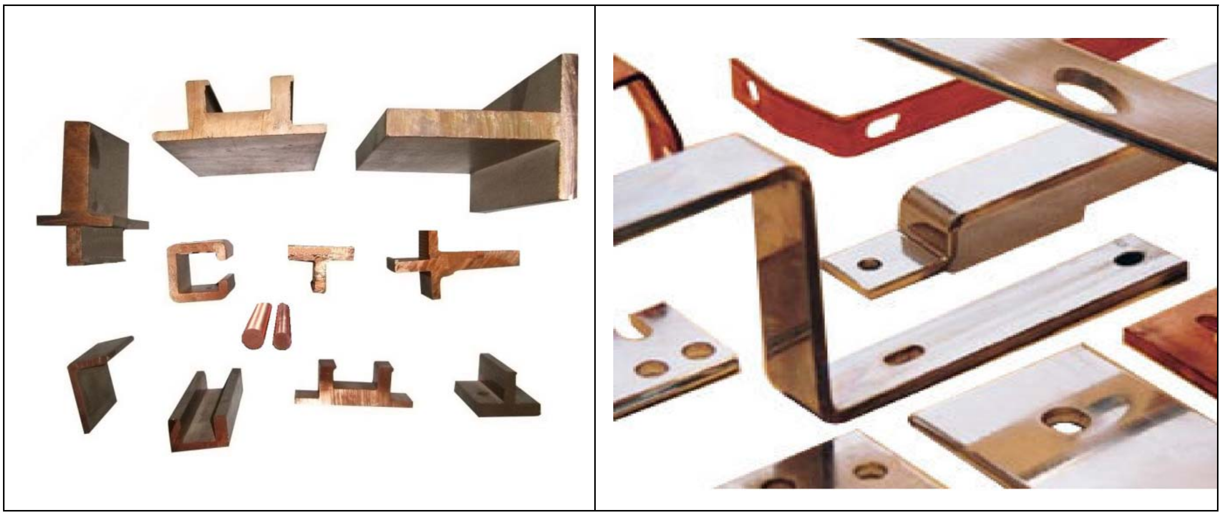


Fig. 3.2-1 Bus-Bar and Cross Section Shapes

Fig. 3.2-2 shows how these different bus bars may be constructed. Note that the bus in Fig. 3.2-2(a) is contained within special tubular covering called **bus duct.**

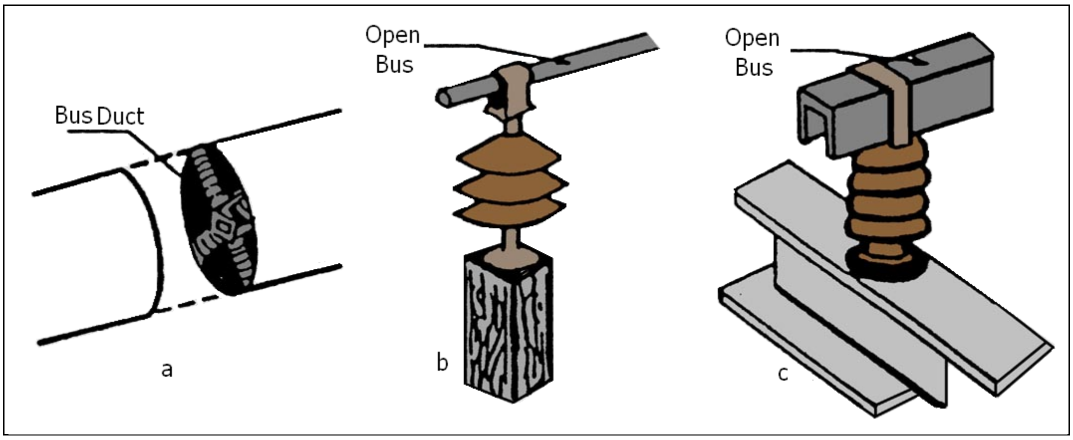


Fig. 3.2-2 Bus-Bar Placements

Its function is to support and protect the bus. Fig. 3.2-2(c) shows an open bus. It consists of series of aluminum tubes mounted on posts with **porcelain** insulators. Fig. 3.2-2(b) is simple open bus structure with copper bars supported on fiber blocks.

BUS DUCTS

The main bus duct runs from the generator(s) to the main transformer, It is a metal sheet pipe that supports and protects the heavy, hollow, square/round copper/aluminum bus. The bus is suspended within the protective duct by means of porcelain insulators. Air vents provide pressure balance and cooling. The air vents are shielded to prevent the possibility of any external object from coming in contact with the bus bar. Each phase of the three-phase generator output is carried in separate duct called isolated phase bus duct. In lower voltage applications, all three phases of the circuit are contained within single protective duct, as shown in Fig. 3.2-3.

Fig. 3.2-3 Isolated Phase Bus Duct

During short-circuits, the magnetic field around the conductors exerts strong force tending to move the conductors toward or away from each other. The conductor

supports must be strong enough to hold the conductor in place during such short circuits. Since most highly conductive metal, such as copper, is relatively soft, special strengthening materials are usually alloyed with the copper mold to make the conductor bus. The bus can be formed to have additional rigidity and physical strength and to provide maximum surface area to increase heat transfer after two or more conductor bars make up single bus element with provision for airflow around all sides. Most designs use tubular, hollow buses made of aluminum. These conductive sections are supported well above the ground by porcelain insulators or bushings. In most isolated phase bus ducts, the insulators, which hold the sections of Bus Bar centered within the duct, to permit small amounts of movement due to temperature changes. This permits some **expansion** and **contraction** of the Bus Bar allowing for momentary physical stress during heavy fault currents. Without such flexibility, any expansion or internal stress could cause serious damage to the bus bar. On the other hand, excess bus movement within the duct could be dangerous. So the amount of flexibility permitted by the design is limited. In low voltage ducts, all phases are assembled together enclosed in one bus duct and there is less need for bus flexibility. In most of these installations, connectors join individual sections. The connectors have provisions for the expansion of long sections of bus, as shown in Fig. 3.2-4.

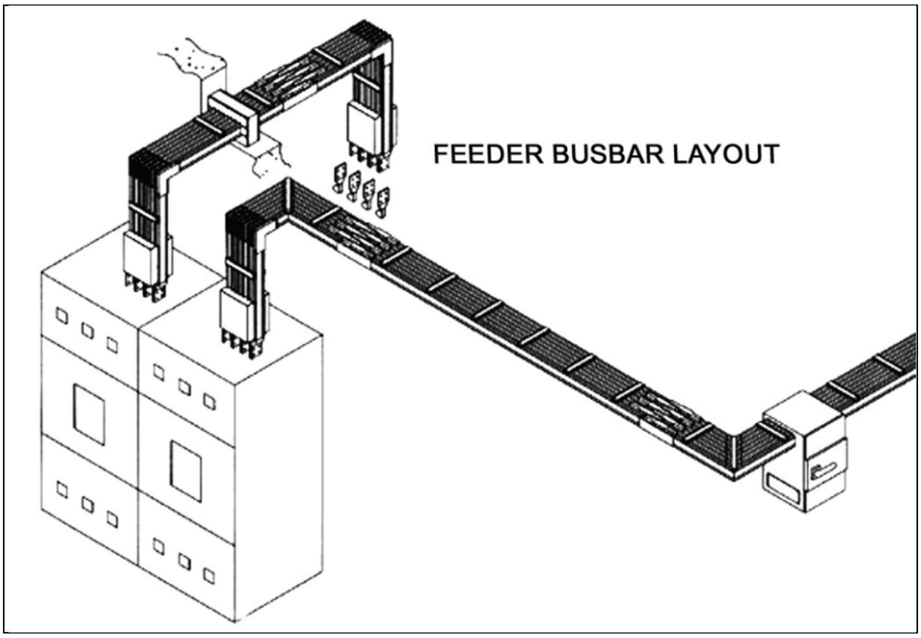


Fig. 3.2-4 Feeder Bus bar System

Fig. 3.2-5 ITE-BBC Bus Duct, enclosing all Three Phases

COOLING OF BUSES AND BUS DUCTS

Power plant buses and bus ducts required, transferring large quantities of electricity from one place to another. Because buses have very low resistance, loss of voltage in buses is less, even under periods of peak loading. The conductors are exposed to air, as shown in Fig. 3.2-4 and Fig. 3.2-5 so that heat is quickly dissipated. The bus support insulators and the surrounding duct jacket provide electrical safety and protection, not only for the bus but also for the plant personnel and equipment. Most installed bus ducts are air-cooled. The duct casing has provisions for outside air to enter and carry away the normal heat build-up in the bus bars within the duct. Where large quantities of energy are being carried, high capacity bus ducts often include forced-air cooling. Filtered air is drawn through the duct to increase heat transfer.

Some high capacity bus ducts include forced hydrogen cooling, very similar to the Stator and Rotor cooling within the generator itself. Some special types of high capacity conductors may not even use bus ducts.

CURRENT CARRYING CAPACITY

Current carrying capacity is the maximum allowable current that can pass through the bus bar. The factor that controls the current rating is safe temperature. The British Standards specify the temperature rise, when carrying normal rated current at rated frequency.

The amount of heat generated in conductor is proportional to its resistance and to the square of the current. The temperature rise depends on the rate, at which the heat is dissipated. Table 3.2-1 shows the current ratings a range of copper and aluminum rectangular Bus Bars based on the proposed metric dimensions and assuming mounted in free air.

Conductor Size (mm)	**Sectional Area (mm^2)**	**Approx. Rating (A)**
2.5 × 12.5	31.25	159
16.0	40.0	195
20.0	50.0	235
63.0	157.5	630
4 × 16.0	64	254
20.0	80	305
25.0	100	367
6.3 × 25.0	157.50	473
31.5	198.45	569
40.0	252.0	693
10 × 50.0	500	1060
63.0	630	1260
80.0	800	1525
16 × 100.0	1600	2220
125.0	2000	2640
160.0	2560	3180

Table 3.2-1 Approximate AC Ratings for Single Rectangular Copper Bars in free air

CLEARANCES

Tables 3.2-2, 3.2-3 and 3.2-4 give the minimum clearances to earth and between phases under different conditions.

Rated Voltage up to and including (kV)	Minimum Clearance to Ground in Air				Minimum Clearance between Phases in Air			
	Open		Enclosed		Open		Enclosed	
	in.	mm	in.	mm	in.	mm	in.	mm
0.415	0.75	19	0.625	16	1	26	0.75	19
0.6	1	26	0.75	19	1.25	32	0.75	19
3.3	2	51	2	51	2	51	2	51
6.6	2.5	64	2.5	64	3.5	89	3.5	89
11.0	3	77	3	77	5	127	5	127
15.0	4	102	4	102	6.5	165	6.5	165
22.0	5.5	140	5.5	140	9.5	242	9.5	242

Table 3.2-2 Clearances for Open and Enclosed Indoor Air Insulated Bus Bars and Connections

Rated voltage up to and including (kV)	Minimum Clearance to Ground		Minimum Clearance between Phases	
	in.	mm	in.	mm
0.6	0.5	13	0.5	13
3.3	0.5	13	0.75	19
6.6	0.75	19	1	26
11.0	1	26	1.5	38
15.0	1.25	32	1.75	45
22.0	1.75	45	2.5	64
33.0	2.5	64	3.5	89

Table 3.2-3 Clearances for Bus Bars and Bus-Bar Connections immersed in Oil

Impulse Voltage withstand Level Peak Value (kV)	Rated Voltage (kV)	Minimum Clearance to Ground in Air		Minimum Clearance between Phases in Air	
		in.	mm	in.	mm
150	22	11	279	13	330
200	33	15	381	17	431
250	44	19	482	22	558
300	50	22	530	26	624
350	66	27	685	31	786
450	88	34	863	39	969
550	110	42	1068	48	1219
650	132	50	1270	58	1473
750	165	58	1473	67	1702
850	190	72	1750	83	2010
1050	220	82	2082	94	2368

Table 3.2-4 Clearances for all Open Outdoor Bus-Bars and Bus-Bar Connections of 22 – 88 kV Rated Voltage and for Grounded Systems of 110 kV and above

INSULATORS

The conductors of overhead transmission (or distribution) lines and bus bars in the substations are secured to the supporting structures by means of insulating fixtures in order that there is no current leakage to the earth through the supports. Thus, the insulators play an important role in the successful operation of overhead transmission or buses in the substations.

The insulators, used for overhead transmission (or distribution) lines and bus bars, must have the following characteristics:

- Mechanically, very strong in order to withstand the load due to the weight of the conductor.

- High dielectric strength and insulation resistance in order to avoid leakage of currents to earth.

- High resistance for flashover.
- The material employed should be non-porous having no effect by change of temperature, such as ceramic materials.

INSULATOR MATERIALS

Porcelain is widely used material. It is mechanically stronger than glass. Its surface is not affected by dirt deposits and is less sensitive to temperature changes. The dielectric strength of porcelain insulators is about 60 kV/cm of thickness.
Glass is cheaper than porcelain in simple shapes and if properly toughened and annealed gives high resistivity and dielectric strength (140 kV/cm). Glass is quite homogeneous material but moisture could condense on its surface and accumulate dirt deposits and thus causing high surface leakage. Glass insulator, however, can be used up to 25 kV under ordinary atmospheric conditions and up to 50 kV in dry atmosphere.

Steatite is magnesium silicate material having higher effect stress and bending stress than porcelain and is used in transmission lines for sharp turns.

OVERHEAD LINE INSULATION

PIN INSULATOR

The pin type insulator is mounted on pin, which in turn is installed on the cross-arm of the pole. The electrical conductor is placed in the groove at the top of the insulator, as shown in Fig. 3.2-6(a).

SUSPENSION INSULATOR

In order to meet the problem of insulator with high voltages, the suspension insulator hangs from the tower and the line conductor is attached to its lower end. Advantages of suspension insulators are:

- Cheaper
- Each unit can withstand 11 kV and more units can be added in series to increase withstanding voltage.
- Any unit can be replaced in case of failure.
- More flexible to hang from the line, as shown in Fig. 3.2-6(b)

STRAIN INSULATOR

The strain insulators consist of an assembly of suspension insulators for high-tension transmission lines, as shown in Fig. 3.2-6(c).

Fig. 3.2-6 Types of Insulators

BUS AND SWITCH INSULATORS

PIN CAP INSULATOR

It is used for switch and bus insulators, as shown in Fig. 3.2-7. It is cemented assembly of one or more porcelain shells with malleable iron cap and base pin. It provides protection from moisture and contamination.

Fig. 3.2-7 Pin Cap Insulator

INDOOR BUS AND SWITCH SUPPORT CLASS

Indoor bus and switch supports have heavy porcelain sections to ensure their electrical reliability to handle heavy mechanical loads, as shown in Fig. 3.2-8.

STATION POST INSULATORS

Fig. 3.2-8 shows examples of station post insulators with different voltage levels.

Fig. 3.2-8 Variable Strength Insulators

SUBSTATIONS

Substations serve as sources of energy supply for the local areas of distribution. Their main functions are to receive energy transmitted at high voltage from the generating stations, reduce the voltage to a value appropriate for local use and to provide facilities for switching. Substations have some additional functions. They provide points where safety devices may be installed to disconnect circuits or equipment in the event of breakdown. Voltages on the outgoing distribution feeders can be regulated at substation. In addition, substation is a place to make measurements to check the operation of various parts of the system.

Some substations are simply switching stations, where different connections can be made between various transmission lines. Substations are high-risk areas to human life and should be treated with utmost care. The substation is the nerve center of distribution network with expensive equipment in one central area. The substations feed the most sub-circuits of distribution network.

TYPES OF SUBSTATIONS

A substation is an intermediate link between the power station where electricity is generated and the consumer who uses this energy.

There are two types of substations:

- Transmission Substations
- Distribution Substations

TRANSMISSION SUBSTATIONS

Transmission Substations are constructed at Generating Stations and at switching points in the transmission system. Transmission substations near generating stations provide means to connect the electric generators to the system and change the generating voltage to higher voltage in order to transmit the power to specific distance, economically.

The transmission substations located at switching points can serve as sources to sub-transmission circuits. Power transformers installed at the substations can change the transmission voltage to sub-transmission voltage.

DISTRIBUTION SUBSTATIONS

Distribution Substations are located near the utilization point in the electric system. The distribution substations change the sub-transmission voltages to lower voltages. Some substations are entirely enclosed in buildings, while others are built entirely in the open. Substations built in the open are usually enclosed by fence for safety reasons. Substation may have the transformers, high voltage switches, circuit breakers, and lightning arresters located outside the substation. The relaying, metering, and control equipment, that outside elements may damage, may be located inside building.

BUS-BAR SYSTEM

The Bus-Bar system selected for any particular application will depend largely on:

- The degree of flexibility of operation required
- The required degree of safety, during the total shutdown
- The relative importance of the location

In the main plants, e.g. Generating Station, Transmission Stations, or Bulk Supply Point (BSPs), the compact Bus-Bar system is nearly always justified. Here, shutdown results in the disconnection of consumers over wide area and system, but enables reconnection in the shortest possible time.

TYPES OF BUS BAR DESIGNS

Buses distribute electric power throughout the plant and to the transmission grid. The bus system may be designed in various configurations to achieve reliability, continuity, and flexibility of service, equipment, system protection, and periodic maintenance.

SINGLE BUS BAR

Fig. 3.2-9 shows single Bus-Bar scheme. This method is generally used for DC switchboards and AC substation or generating stations. If at any time Bus Bar fault occurs, all feeders will be out of service. Bus Bar cleaning and maintenance sustains complete safety during shutdown.

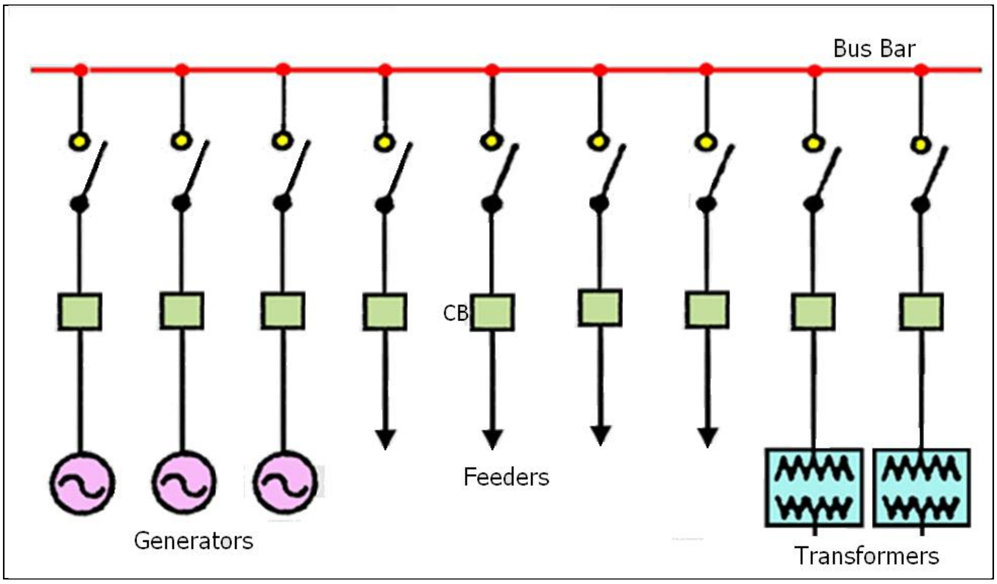


Fig. 3.2-9 Single Bus-Bar System

SECTIONALIZED SINGLE BUS-BAR

Fig. 3.2-10 shows the block diagram of sectionalized bus. It consists of two generators or two supplies providing power to single main bus. The main bus is split into two sections, Bus 1 and Bus 2 by tie Circuit Breaker, which is called **Bus Tie**. This provides complete shutdown of one section for maintenance or repair without interfering with supply from other sections. The number of sections will largely depend on the system requirements of the station.

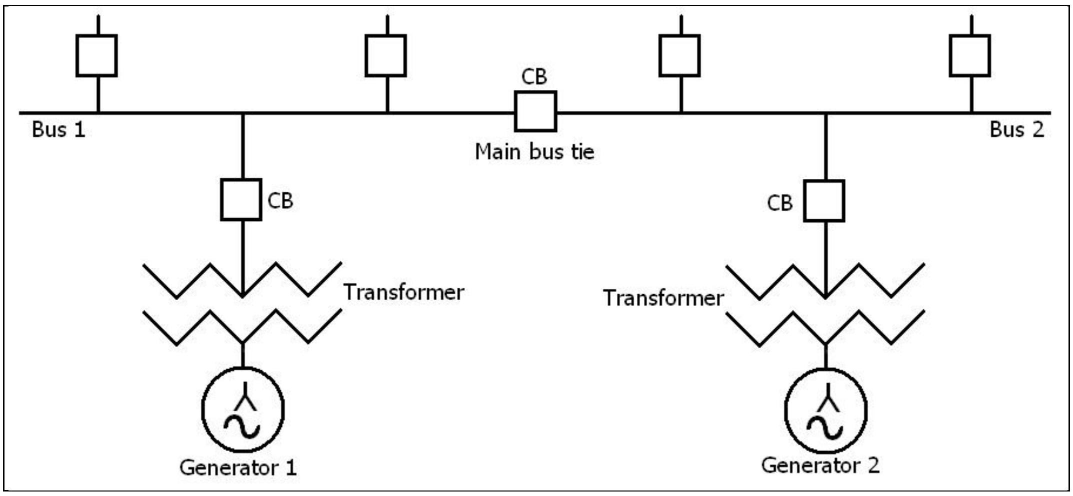


Fig. 3.2-10 Sectionalized Bus Design

To give greater flexibility is to join the ends of multi section Bus Bar, as shown in Fig. 3.2-11. By this means, generating plant on any section can be utilized to supply the feeders on any adjacent section.

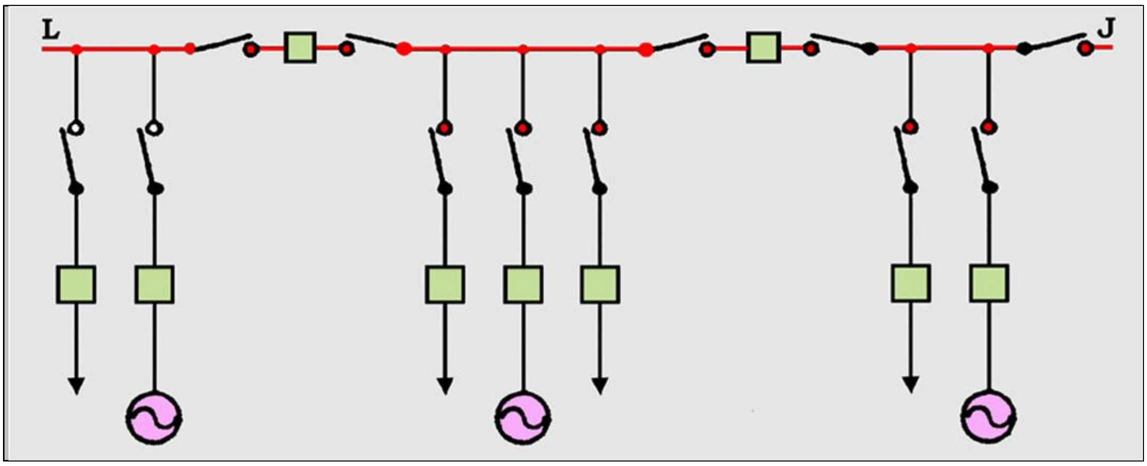


Fig. 3.2-11 Sectionalized Bus-Bar System

MAIN AND TRANSFER BUS

The transfer bus is the one, in which one circuit at a time can be transferred from the main bus, as shown in Fig. 3.2-12.

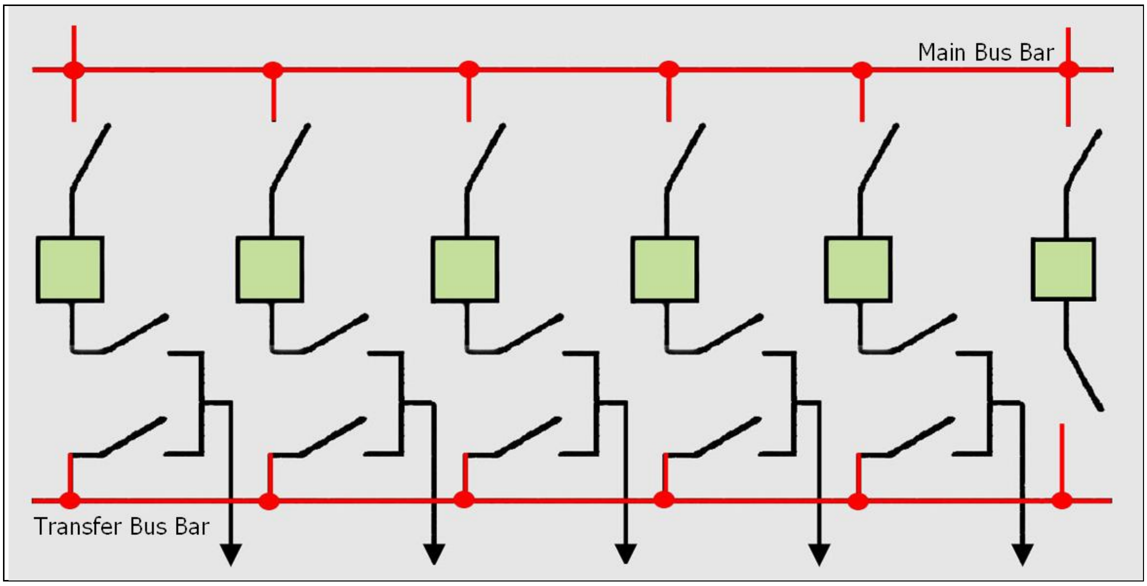


Fig. 3.2-12 Main and Transfer Bus

The transfer bus provides means for servicing the feeder breaker. It would not ordinarily be in use. During an outage of the main bus equipment, however, the lines can be transferred to the T-bus. Because T-bus normally has only one supply circuit breaker, it can handle only one circuit at a time. Fig. 3.2-13 shows an example of two main buses and one transfer bus used in many substation configurations.

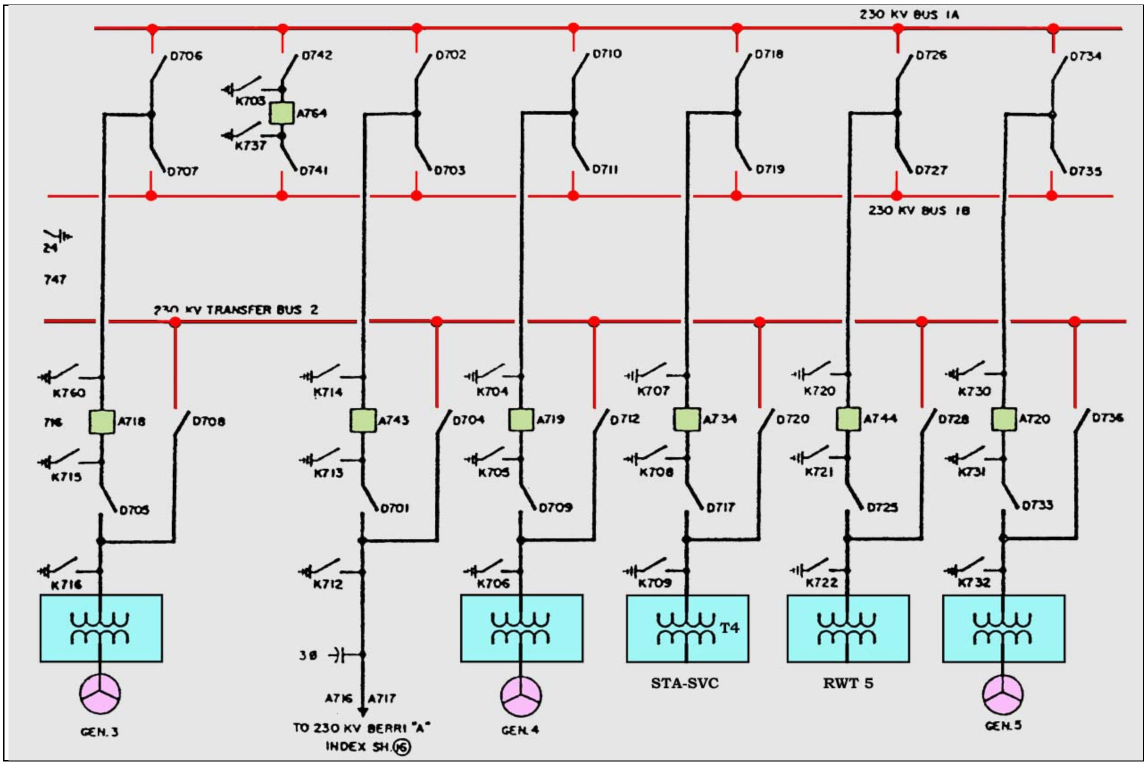


Fig. 3.2-13 Two Main Buses and One Transfer Bus

DOUBLE MAIN BUS

In the applications where it is desirable to duplicate facilities in the substation, the double main bus is installed, as illustrated in Fig. 3.2-14. Each load can be supplied from either bus. Sometimes, half feeders are fed from Bus No. 1 and the other half are fed from Bus No. 2. Both sets of equipment usually are kept in service at all times. Thus, if either should fail, interruption does not occur to the connected facilities. Duplicate facilities double the cost of buses and switching but such added expense can be justified in cases where service reliability is essential. The double main bus scheme is simple and straightforward, minimizing the chance of operating errors, particularly

since all switching is done by Circuit Breakers. Breaker or bus can be taken out of service at any time without interruption of service or loss of line relay protection. If both buses are kept normally energized, fault in either bus can be cleared by differential relays without loss of service.

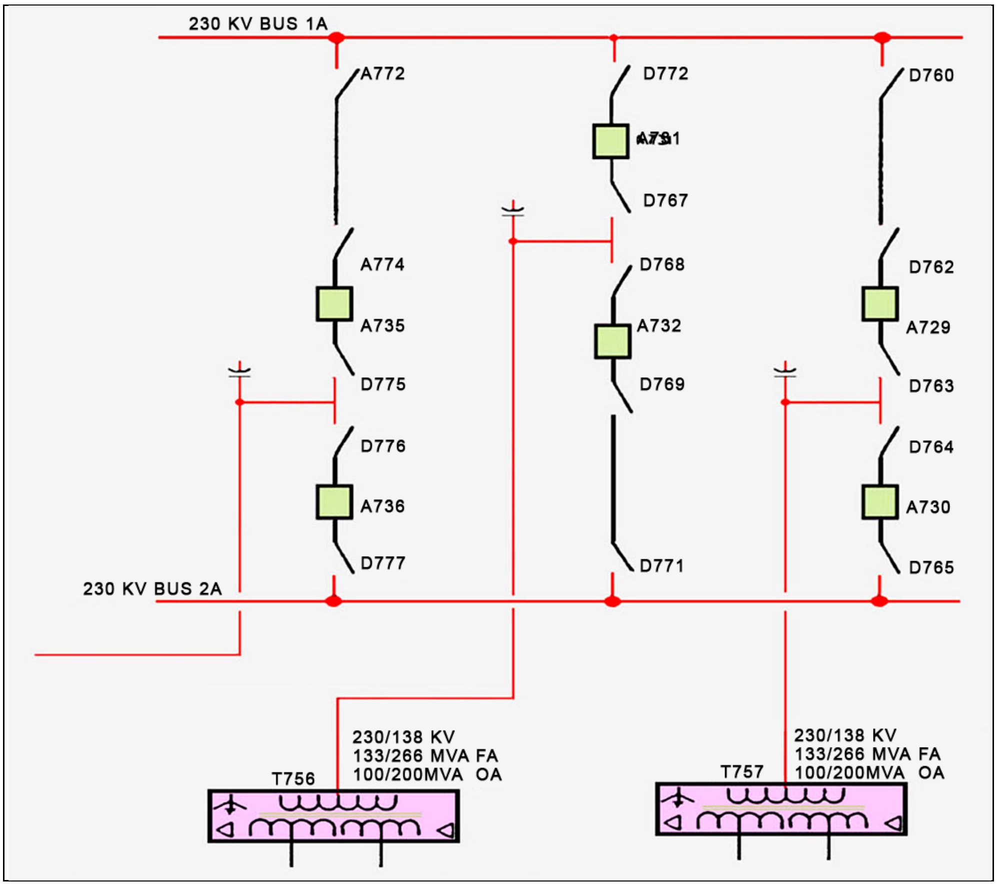


Fig. 3.2-14 Double Main Bus with Double Breaker Design

The standard basic double bus scheme can be modified in number of ways. One or both buses can be divided into any number of sections desired, using bus sectionalizing breakers with isolating disconnecting switches. Fig. 3.2-14 shows an example of Double Main Bus in a typical substation.

RING BUS DESIGN

Fig. 3.2-15 shows an example of Ring Bus used in a typical substation.

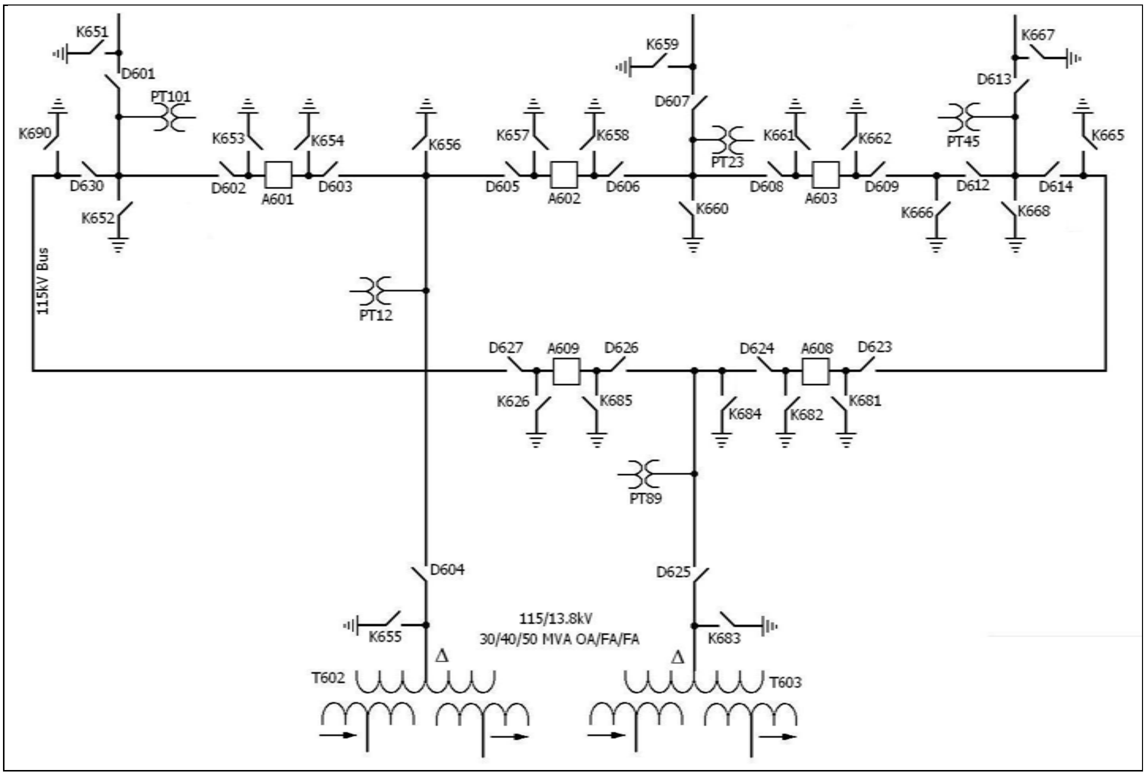


Fig. 3.2-15 Ring Bus Design Example

DOUBLE BUS AND SINGLE BREAKER

Fig. 3.2-16 shows another design, named Double Bus & Single Breaker. This arrangement consists of two buses, and each line or feeder uses single breaker and two disconnect switches. In addition, the arrangement includes Bus-Tie breaker (Bus coupler) to connect the main two buses together. This arrangement allows one feeder to transfer from Bus No. 1 to Bus No. 2 without switching the feeder off by disconnect switch. All feeders may be supplied from the main Bus No. 1 or half of feeders could be supplied from feeder No. 1 and other half from feeder No. 2.

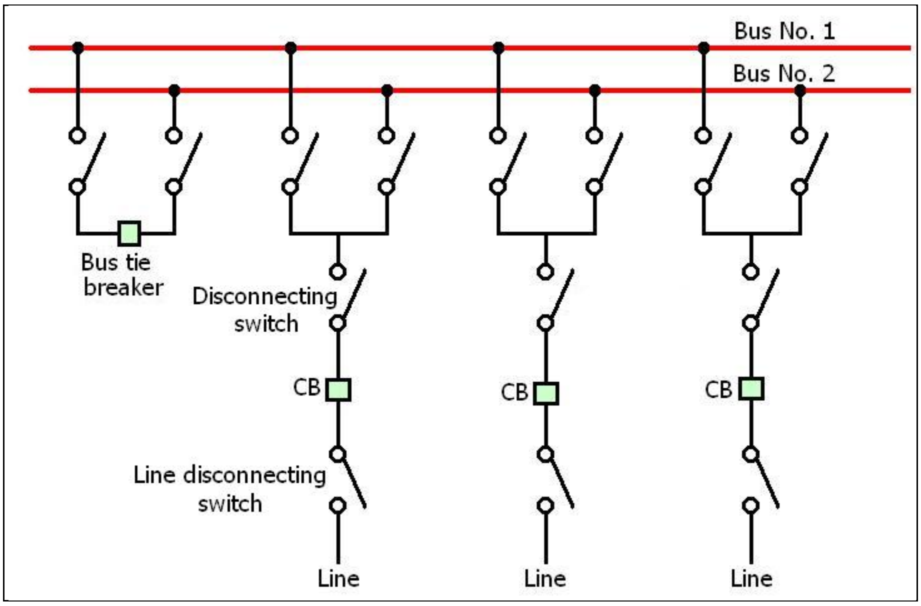


Fig. 3.2-16 Double Bus & Single Breaker Design

BREAKER AND HALF DESIGN

Fig. 3.2-17 shows another design, named **Breaker and Half Design,** and sometimes named three breakers scheme. This scheme includes three breakers in series between the two main buses and two feeders are fed from the three breakers and, hence, the scheme named breaker and half.

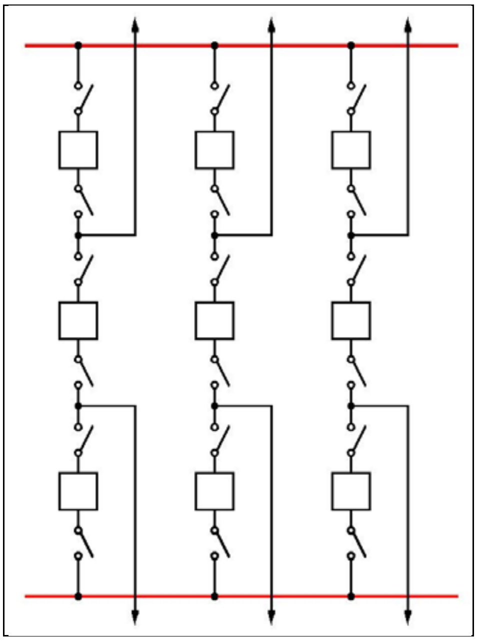


Fig. 3.2-17 Breaker and Half Scheme

In the normal operation, all the breakers are ON and both buses 1 and 2 are energized. In case of a problem for any bus, all the feeders will be fed from the other bus, automatically. Fig. 3.2-17 shows an example of Breaker and Half Scheme.

SWITCHGEAR IDENTIFICATION AT SUBSTATION

All switchgears are identified by letter and number code. Each piece of equipment has its own identification code. This identification consists of single letter and three-digit number. The letter identifies the type of equipment, as follows:

A	230 kV to 69 kV Circuit Breaker (power switchgear)
B	13.8 kV Circuit Breaker (distribution switchgear)
D	Disconnect switch
K	Grounding (Earthing) switch

The first number in the three-digit number identifies the voltage of the equipment, as follows:

3	13.8, 11 kV
4	34.5 kV
5	69 kV
6	115 kV
7	230 kV
8	380 kV

The last two numbers indicate the sequence number, as follows:

A714	230 kV Circuit Breaker Number 14
D720	230 kV Disconnect switch Number 20
K77	230 kV Grounding (Earthing) switch Number 7

SUMMARY

- Bus Bars have many shapes like tubes, bars, or cables.
- The bus duct is a sheet metal pipe that supports and protects the heavy, hollow, square/round copper/aluminum bus.
- The bus support insulators and the surrounding duct jacket provide electrical safety and protection, not only for the bus but also for the plant personnel and equipment.
- The amount of heat generated in a conductor is proportional to its resistance and to the square of the current and the temperature rise depends on the rate, at which the heat is dissipated.
- The Glass insulators can be used up to 25 kV under ordinary atmospheric conditions and up to 50 kV in dry atmosphere.
- **Steatite** is magnesium silicate material having higher tensile stress and bending stress than porcelain material and is used for insulators in transmission lines for sharp turns.
- Voltages to consumers in distribution system can be regulated and monitored at substations.
- A substation is an intermediate link between the power station where electricity is generated and the consumer who uses this energy.
- A sectionalized bus is split into two or more sections separated by bus-tie circuit Breaker(s) with generators or incoming feeder providing power to the sections of the single main bus.
- A sectionalized bus provides complete shutdown of one section for maintenance or repair without interfering with supply from other sections.

GLOSSARY

BSP	Bulk Supply Point
T-Bus	Transfer Bus
Bus ducts	Isolated bus bar inside tube
Bus tie	Connection between two bus sections
Ring bus bar	Connection between bus bars in closed loop
Steatite	Type of smooth skin insulator
Malleable iron	Soft iron used in different applications
Toughened:	Made hard or rigid
Annealing:	Hardening process

REVIEW EXERCISE

1. Bus Bars are normally made of ____________ or ______________.

2. An isolated phase bus duct carries each phase of the three-phase generator output in separate duct.

   a) True   b) False

3. The high capacity buses ducts are often utilize ____________ cooling, where filtered air is drawn through the duct to increase heat transfer.

5. List the characteristics of insulators used for overhead transmission (or distribution) lines and bus-bars:

   a) ____________________________   b) ____________________________

   c) ____________________________   d) ____________________________

6. The dielectric strength of **porcelain** insulators is about _____ kV/cm of thickness.

   a) 60   b) 75

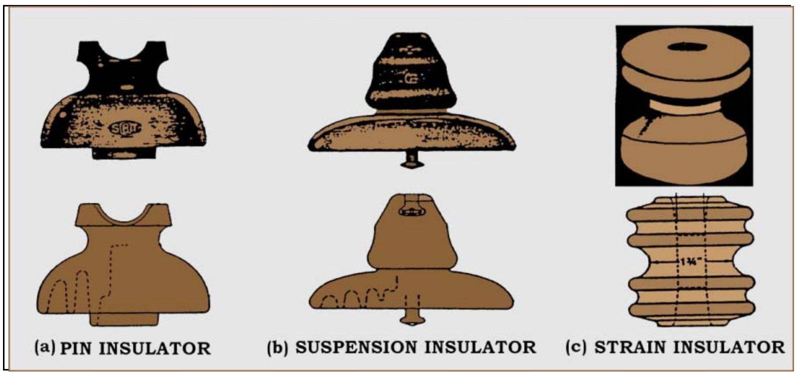
   c) 15   d) 140

7. The dielectric strength of **Glass** insulators, if properly toughened and annealed, gives high resistivity and dielectric strength of _____ kV/cm).

   a) 60   b) 75

   c) 15   d) 140

8. Identify the insulators in figure below.



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9. A Substation is a source of an energy supply for a local area of transmission, where measurements are made to check the operation of various parts of the system.

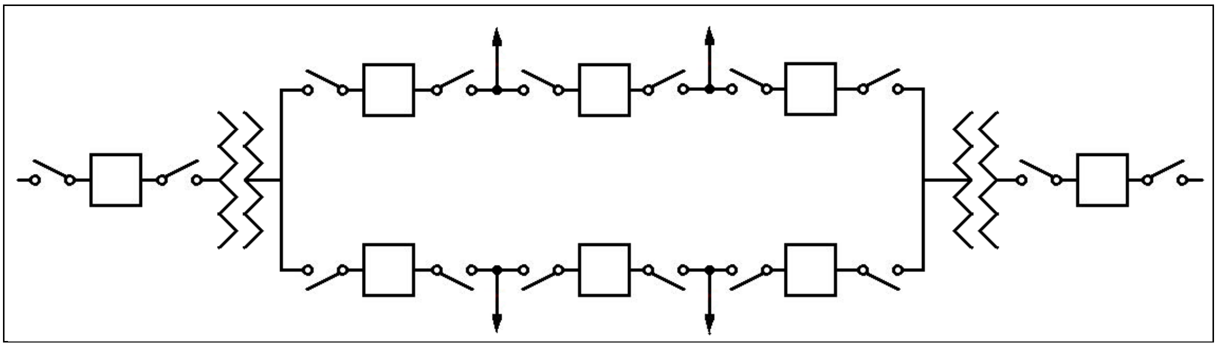
   a) True b) False

10. The two types of substations are:

    a) ______________________ b) ________________________

11. The Buses distribute electric power throughout the plant and to the ________________________________.

12. Identify the bus type for each of the following bus bar systems.



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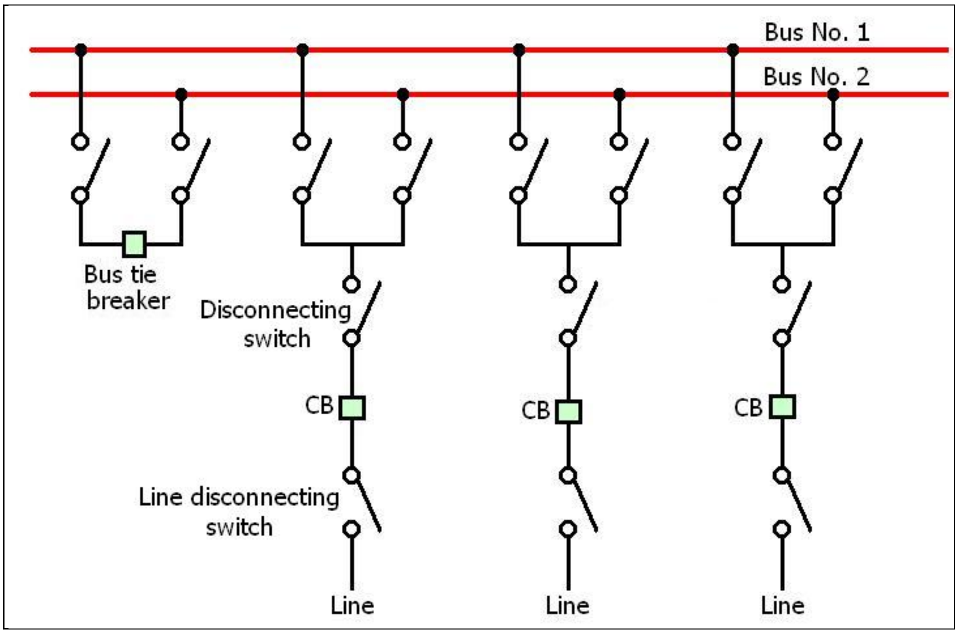

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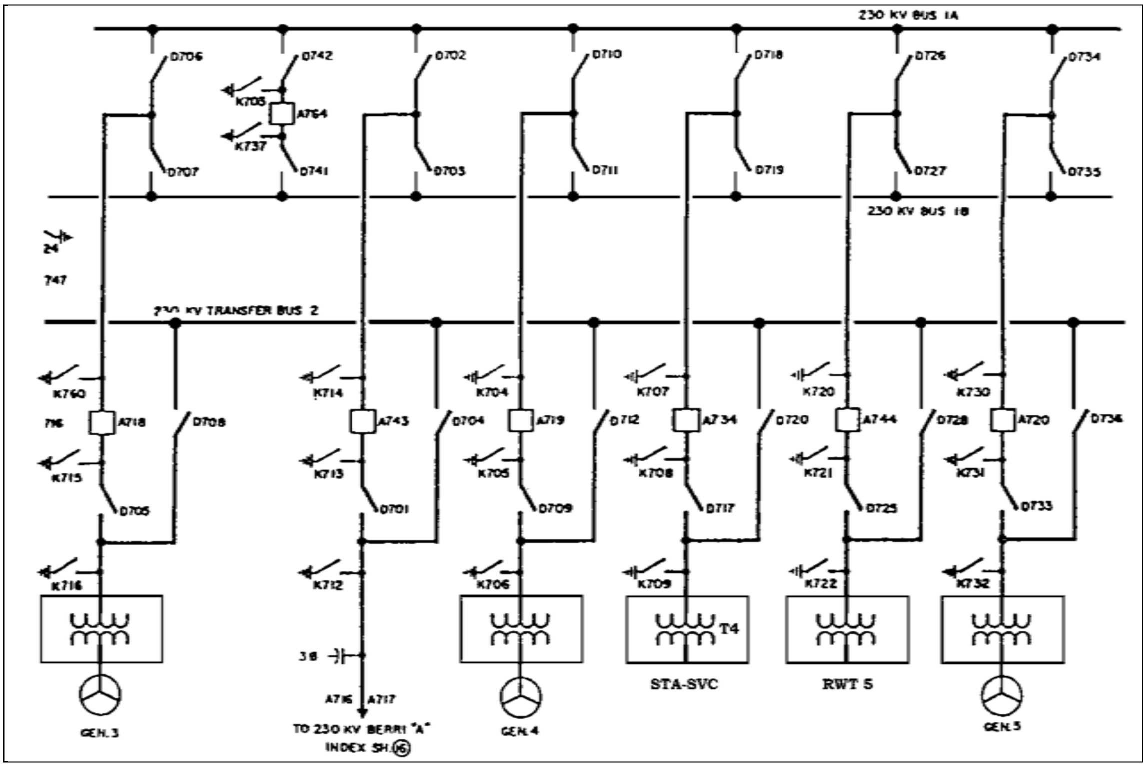
230 KV BUS 1A
230 KV BUS 1B
230 KV TRANSFER BUS 2
D706
D707
D742
D741
A764
K705
K737
D702
D703
D710
D711
D718
D719
D726
D727
D734
D735
747
K760
A718
K715
D705
D708
K716
K714
A743
K713
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D704
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K709
K720
A744
K721
D725
D728
K722
K730
A720
K731
D733
D736
K732
T4
STA-SVC
RWT 5
GEN. 3
GEN. 4
GEN. 5
A716
A717
TO 230 KV BERRI "A"
INDEX SH.16

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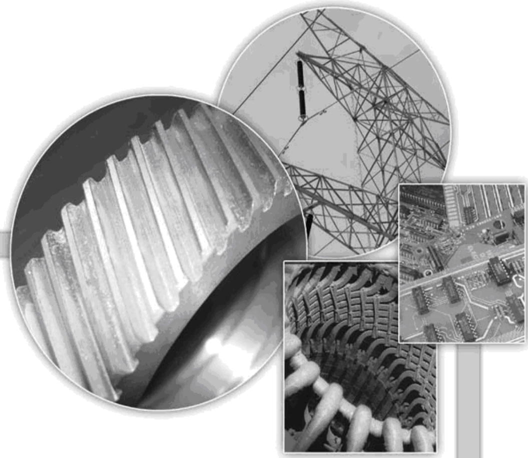


LESSON 3.3

PROTECTIVE EQUIPMENT

LESSON 3.3
PROTECTIVE EQUIPMENT
(FUSES & ARRESTERS)

OVERVIEW

This lesson familiarizes the trainees with the different types of fuses and lightning arresters as protective equipment against voltage surges in the power system.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Explain principles of operation and types of fuses.
- Identify the types and function of lightning arrester.
- Demonstrate the function of discharge counter.
- Verify the procedures for cleaning of lightning arrester.

INTRODUCTION

Fuses are economical protective devices that connected in series with the circuits to protect the circuits and other connected equipment against damage due to overload or short-circuit. Among all types of protective devices of electrical system and equipment, fuses are the simplest and least costly. Fuses are used for all voltages in all areas of electrical power transmission and distribution. Fuses and lightning arresters are installed to minimize the customer power outages.

FUSE PRINCIPLE

The fuse consists of a fusible element and a casing. The fusible element carries the current. The word fusible means "capable of being melted by heat." When current **(I)** flows through a resistance **(R)**, heat is produced. Heat expressed as Power loss is measured in Watts. The fusible element in a fuse melts when the current (and resultant heat) exceeds a rated value for a certain length of time. It usually consists of a short piece of wire made of lead or more often of an alloy of lead and tin, which will melt at high temperature. The current flow through such a metal develops enough heat to melt the metal and open the circuit before the abnormal (high) current can damage the circuit or other connected equipment.

Fuses are usually enclosed in a case to prevent the molten metal from flying and causing damage or a fire. Enclosing the fuse also helps to quench the arc in the absence of air. The melting of the fuse is often accompanied by a puff of smoke of vaporized metal.

TYPES OF FUSES

There are two types of fuses:

- Low voltage fuse.
- High voltage fuse.

LOW VOLTAGE FUSE

The most used at low voltage is the plug type fuse, and almost universally used for residential services and for ordinary lighting branch circuits on domestic panel boards. The fuse consists of a small cup of porcelain within which the fusible wire connects the center contact with the outer metal screw shell, as shown in Fig. 3.3-1. Plug fuse is screwed in a socket. Fusible element is contained in porcelain cup. Cup has transparent cover to permit inspection of fusible element.

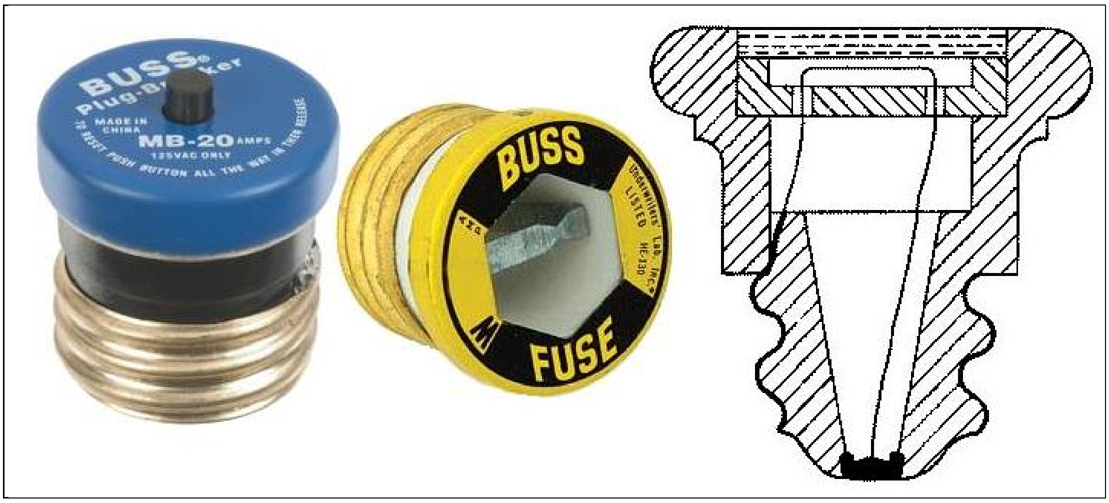


Fig. 3.3-1 Plug Type Fuse

HIGH VOLTAGE FUSE

High voltage fuses are used on power systems up to 115kV AC. High-voltage fuses are used to protect instrument transformers used for electricity metering, or for small power transformers where the cost of a circuit breaker is not acceptable.

Large power fuses use fusible elements made of silver, copper or tin to provide stable and predictable performance. High voltage high power fuses are standalone protective switching devices used for 115 kV line protection. They are used in power supply and distribution networks. The most frequent application is in transformer circuits, with further uses in motor circuits and capacitor banks. These types of fuses may have a problem to operate a switch mechanism. Therefore, all three phases are interrupted if

any fuse blows. “High-power fuse" means that these fuses can interrupt several kilo amperes. Types of high voltage fuses are shown in Fig. 3.3-2.

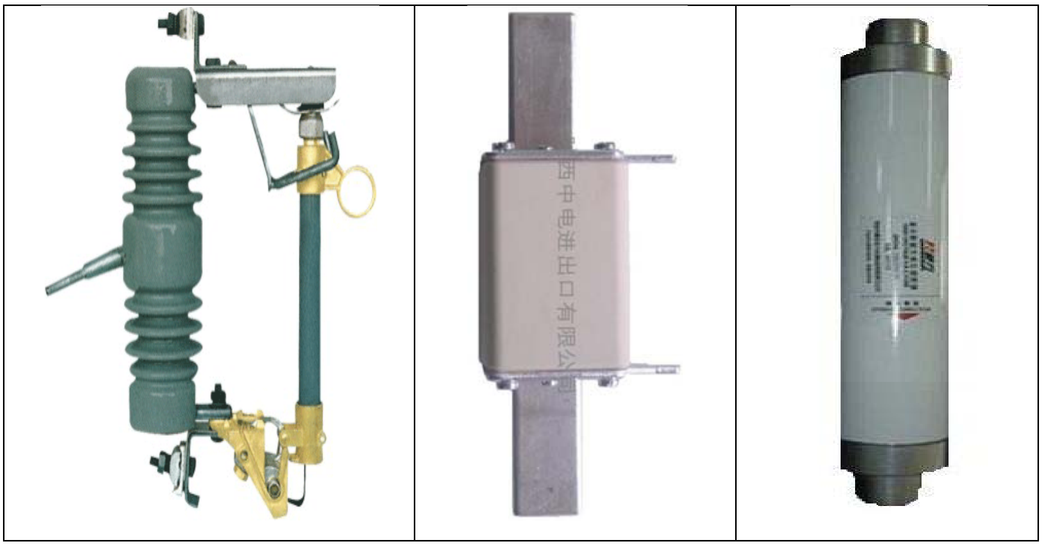


Fig. 3.3.2 High Voltage Fuses

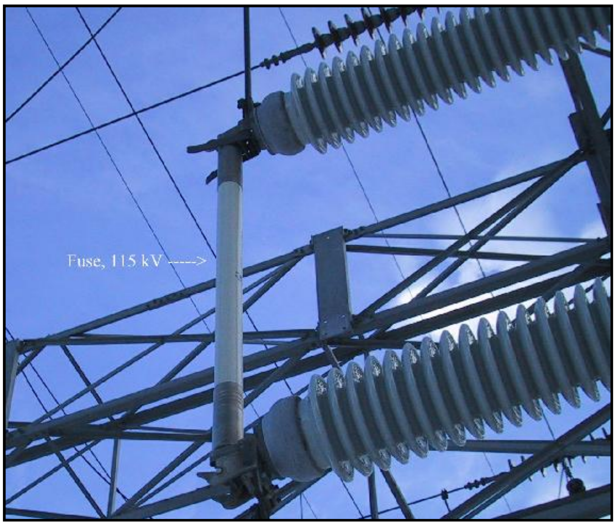


Fig. 3.3-3 HV Fuse Connected in 115kV Substation

LIGHTNING ARRESTERS

Lightning arresters are used as overvoltage protection devices to protect the electrical system and substation equipment from lightning strikes. Arresters must be installed as close as possible to the protected objects.

AC Surge arresters are made from a material that exhibit non-linear resistance.

NON-LINEAR RESISTANCE OF ARRESTER ELEMENT

The arrester element at normal operation offers very high resistance and no current flow through it. At surge voltage occurs, the arrester element decreases its resistance to very small resistance, result in current passes through the arrester until the surge is gone and the arrester resistance return to grow again.

That is, the resistance of the arrester is inversely proportional to the surge voltage. To begin with, an ideal arrester should have infinite resistance when the voltage across it is normal and zero resistance when the voltage exceeds the turn on voltage. Practically, the ideal voltage-current relationship is difficult to achieve. The first generation of over-voltage protection devices was simple spark gaps, where the spacing was designed so that the gap broke down during surge conditions.
The next innovation was the gapped **Silicon Carbide** arrester that used blocks of silicon carbide in series with a spark gap. Silicon carbide exhibits non-linear resistance, but under surge conditions, the resistance across the arrester element was too low and permitted hundreds of Amps to flow to ground. A series gap is added so that the entire voltage appears across the gap in normal conditions. When a surge occurs, the gap breaks down and the surge shorts to ground through the silicon carbide blocks. After the surge is over, the silicon carbide blocks would limit the current to a value, which the gap could naturally extinguish. Lightning arresters provide low impedance path to switching surges or overvoltage transients to ground the lightning or transient currents and then restoring normal circuit conditions.

Lightning arresters serve the same purpose on a line as a safety valve on a steam boiler. A safety valve on a boiler relieves a high pressure by blowing off steam until the high pressure is reduced to normal. When the pressure is down to normal, the safety valve closes again and is ready for the next abnormal condition. Such is also the operation of a lightning arrester.
When a high voltage, greater than the normal line voltage, appears on the line, the arrester immediately furnishes a path to ground and thus drains off the excess voltage.

Fig. 3.3-4 Lightning Arresters in Action

Furthermore, when the excess voltage is relieved, the action of the arrester must prevent any further flow of power current to ground. The function of a lightning arrester is, therefore, two-fold, first to provide a point in the circuit at which the lightning impulse can pass to earth without injury to line insulators, transformers, or other connected equipment, and second to prevent any follow-up power current from flowing to ground.

Fig. 3.3-5 Lightning Arrester

Transformers that are connected directly to the overhead lines have a good chance of being subjected to high lightning surges. The lighting arrestors are installed with the power equipment especially the outdoor types located at higher altitudes. Some of lightning arrestor is shown in Fig. 3.3-5.

TYPES OF LIGHTNING ARRESTERS

There are several types of lightning arresters in general use. They differ only in constructional details but operate on the same principle via, providing low resistance path for the surges to the ground. Following are the different types of lightning arresters:

1- Rod arrester
2- Horn gap arrester
3- Expulsion type lightning arrester
4- Valve type lightning arrester

ROD TYPE ARRESTER

These rods are mounted in a high place to protect station buildings and installations by diverting the lightning strokes to earth.

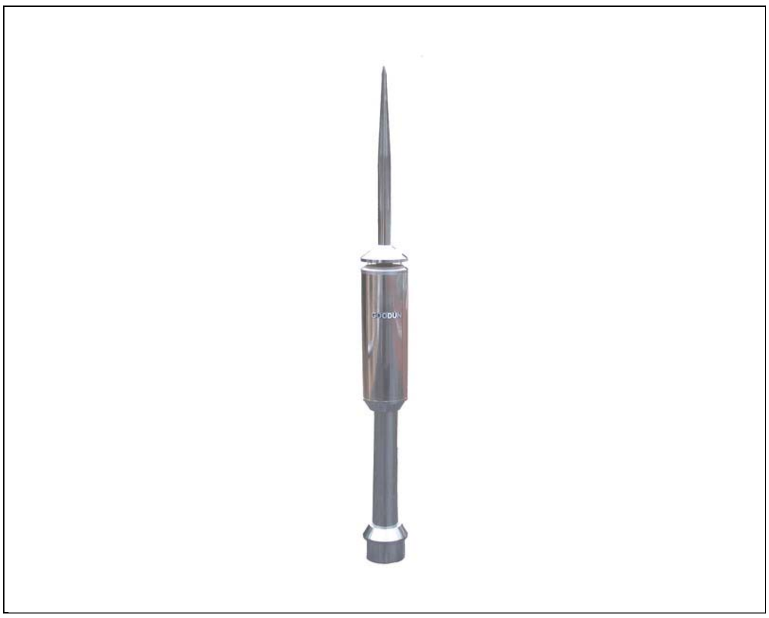


Fig. 3.3-6 Rod Type Arrester

HORN GAP ARRESTER

H**orn gap arrester** consists of a horn shaped metal rods separated by a small air gap. The horns are so constructed that distance between them gradually increases towards the top as shown. The horns are mounted on porcelain insulators. One end of horn is connected to the line through a resistance while the other end is effectively grounded. The resistance R helps in limiting the follow current to a small value. The choke coil is so designed that it offers small reactance at normal power frequency but a very high reactance at transient frequency. Thus the choke does not allow the transients to enter the apparatus to be protected. The gap between the horns is so adjusted that normal supply voltage is not enough to cause an arc across the gap.

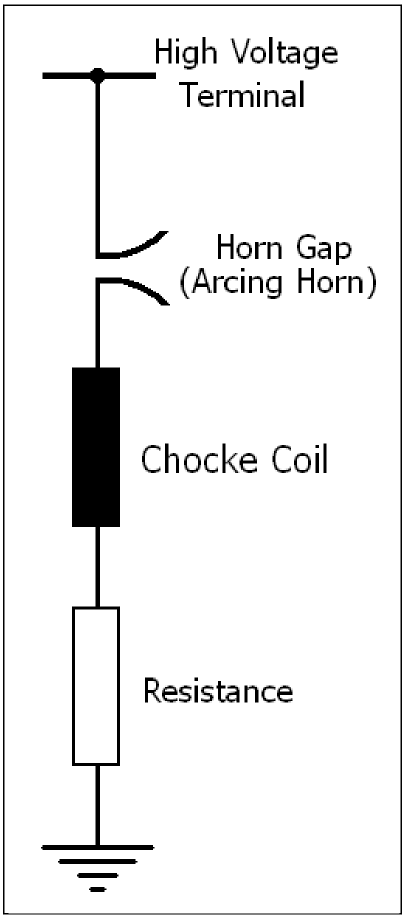


Fig. 3.3-7 Horn Gap Arrester

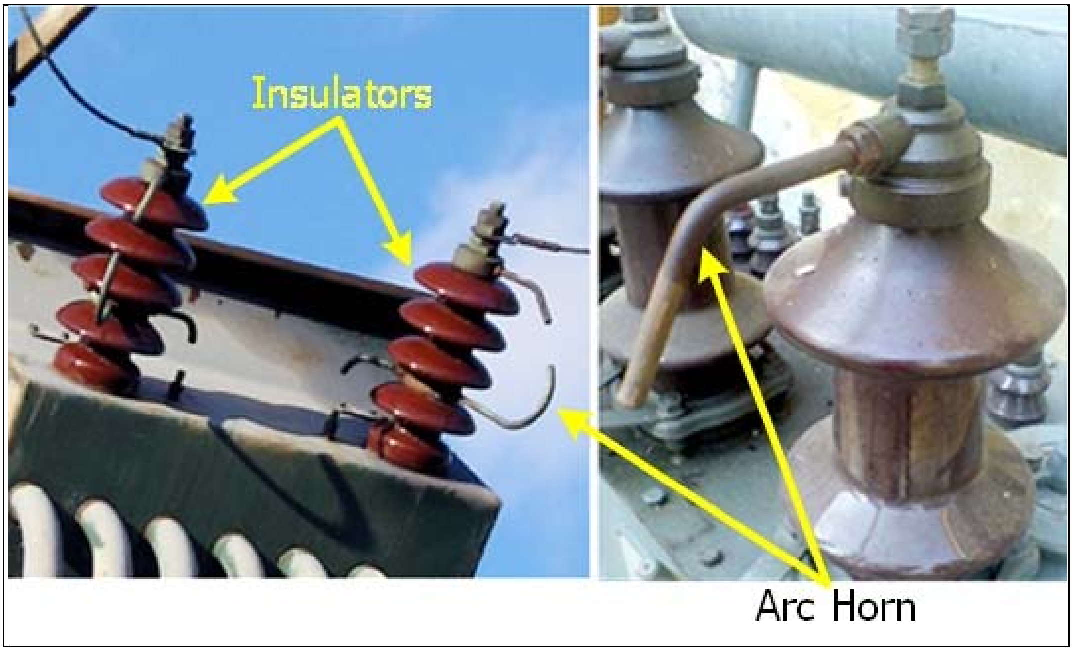


Fig. 3.3-8 Arcing Horn Gap Used with Transformer Bushings

EXPULSION TYPE ARRESTER

This type of arrester is commonly used on system operating at voltages up to 33kV. Fig. 3.3-8 shows the essential parts of an **expulsion type lightning arrester**. It essentially consists of a rod gap AA' in series with a second gap enclosed within the fiber tube. The gap in the fiber tube is formed by two electrodes. The upper electrode is connected to rod gap and the lower electrode to the earth. One expulsion arrester is placed under each line conductor. Fig. 3.3-8 shows the installation of expulsion arrester on an overhead line. It is commonly mounted on the bushings of transformers.

VALVE TYPE ARRESTER

The auto-valve arrester consists of a permeable block, which is the auto-valve element connected in series with a spark gap. Both units are enclosed in a porcelain or polymer case as shown in Fig. 3.3-9, with the internal construction of a distribution-type auto-valve arrester. The auto-valve element is made of a mixture of ceramic material and conducting particles.

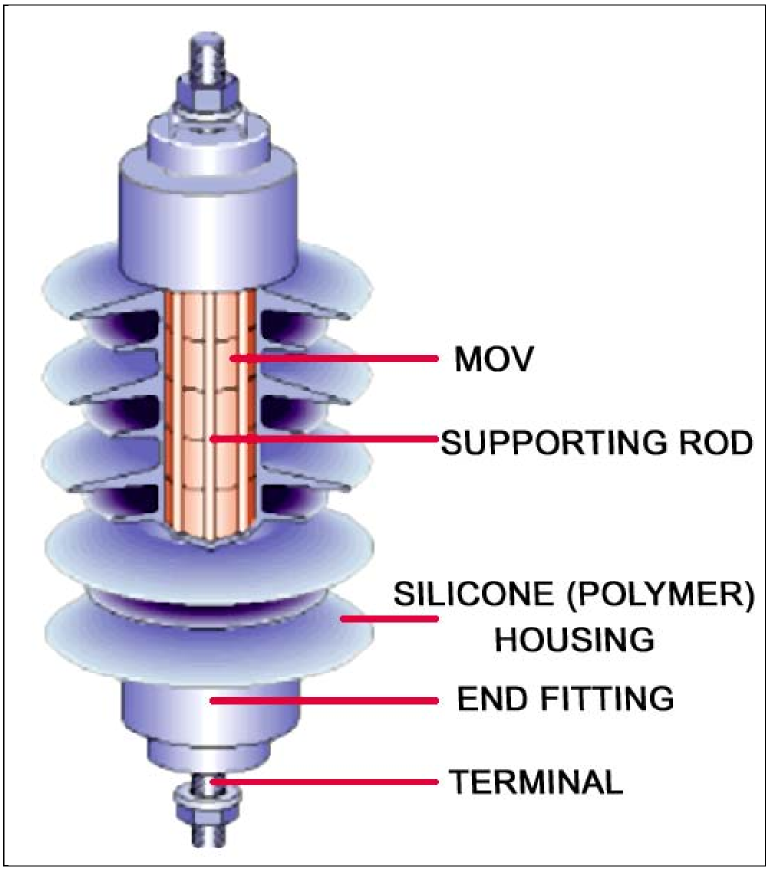


Fig. 3.3-9 Auto-Valve Polymer Type Arrester

This arrester is similar to other arresters in that the valve element has the special property of conducting the lightning surge with great freedom but offering high resistance to the passage of power current. When lightning strikes the line, the high voltage causes the valve element to become readily conducting, thus quickly draining off the lighting charge.

METAL OXIDE TYPE ARRESTER

This type of arrester consists of stacked Thyrite disks connected in series with a gap, and these two elements are enclosed in a porcelain tube covered on both ends with aluminum castings.

EXAMPLES OF LIGHTNING ARRESTERS USED IN SEC

SURGE ARRESTER TYPE HM (BBC)

Fig. 3.3-10 shows surge arrester types HML, HMM, HM. These arresters have rated discharge current of 10 kA

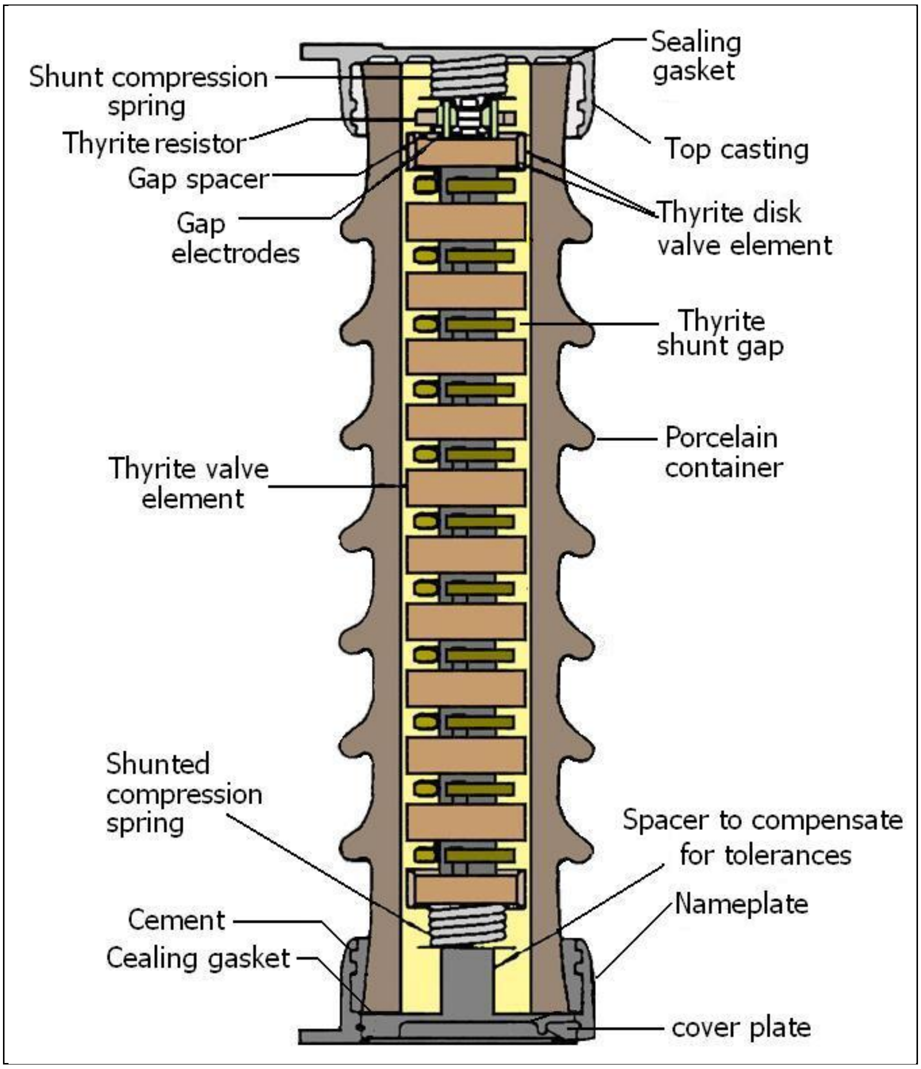


Fig. 3.3-10 Metal Oxide Lightning Surge Arrester Type HM

Fig. 3.3-8 shows surge arrester location in substation switchyard with insulated base fitting.

Fig. 3.3-11 Surge Arrestor Location in Substation

DISCHARGE COUNTER

Discharge counter is used in conjunction with surge arrester for recording and monitoring of lightning discharges in the system and to determine how often the surge arrester sparks over and detecting possible faults. Fig. 3.3-12 show counter circuit diagram.

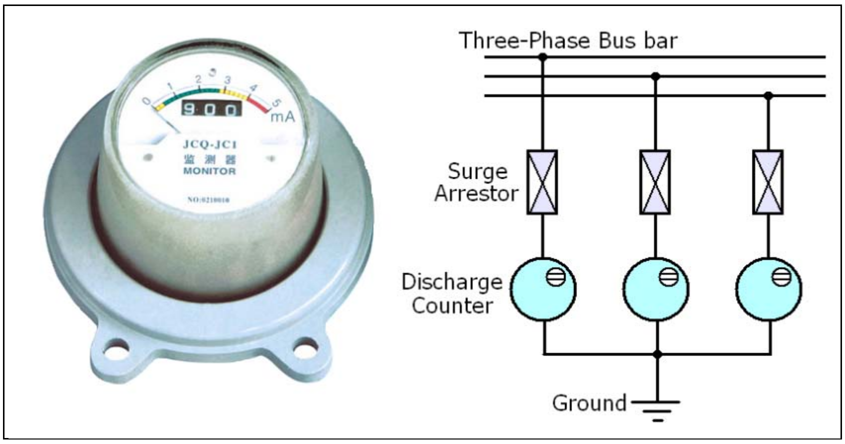


Fig. 3.3-12 Arrestor Discharge Counter

The counting relay **(Z)**, the capacitor **(C)** and the nonlinear absorbed resistor **(R_1)** are connected across the protective spark-gap **(F)** and the second non-linear resistor **(R_2)**. If an impulse causes the surge arrester **(2)** to spark over, capacitor **(C)** is charged up through resistor R_1. On reaching a certain voltage, the spark-gap **(F)** breaks down so that during the rest of the discharge operation, the current flows to earth **(4)** through

resistor R_2. The charged capacitor **(C)** discharges through the counting relay **(Z)**, whose armature drives the actual counting mechanism.

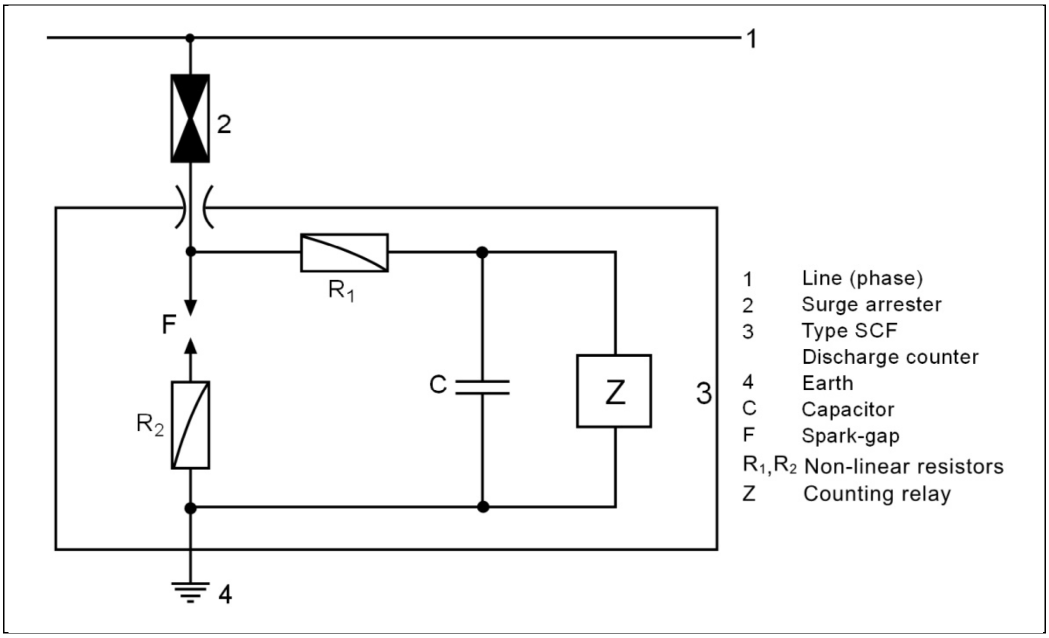


Fig. 3.3-13 Schematic Diagram of Type SCF (BBC) Discharge Counter

The elementary form of an arrester is a simple horn gap connected in series with a resistance, as shown in Fig. 3.3-12.

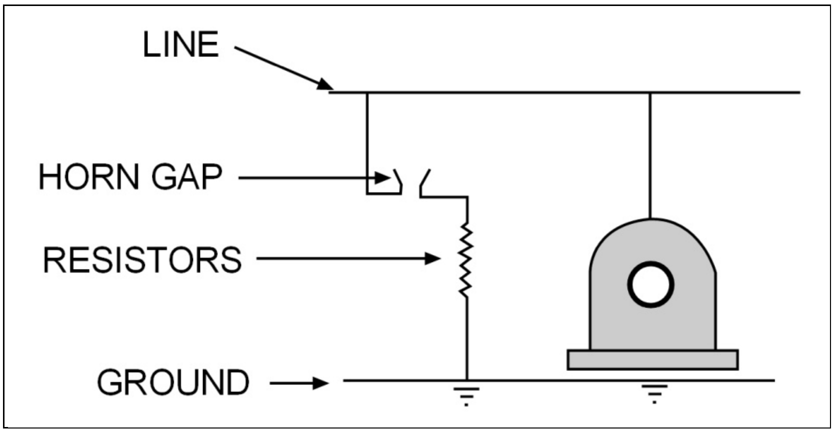


Fig. 3.3-14 Elementary Lightning Arrester

SUMMARY

- Fuses are inexpensive protective devices connected in circuits to protect the circuits and other connected equipment from damage due to overload or short-circuit.
- The fusible element in a fuse melts when the current (and resultant heat) exceeds a rated value for a certain length of time.
- Valve type lightning arrester consists of a non-linear resistive element.
- Arrester element is represented with non linear resistance.
- Metal oxide lightning surge arrester is the most widely used type for HV protection.
- The elementary form of an arrester is a simple horn gap connected in series with a resistance.
- Thyrite arrester consists of stacked Thyrite disks connected in series with a gap, enclosed in a porcelain tube covered on both ends with aluminum castings.

GLOSSARY

Lightning:	Huge static electric discharge from thundering clouds to ground.
Surge Arrestor:	Protective device against high surge voltage
Plug Fuse:	Type of screw in fuse
Thyrite Arrestor:	Type of arrestor material
Non-linear resistance:	Decreasing resistance with increasing voltage surges.
Metal oxide arrester:	Type of stacked elements of arrester
Fuse Element:	Type of metal wire melts during fault
Discharge Counter:	Records number of arrestor actions
Horn Gap:	To discharge for lightning surge

REVIEW EXERCISE

Circle the letter a, b, c or d that correctly completes the statement

1. A fuse is a protective device in a circuit that ____________________.
   a) is used for transforming unsafe current to safe value
   b) when full load current passes for a long time it will interrupt the circuit
   c) protects the circuit components from excessive current flow more than that designed for
   d) interrupts the circuit at under-voltage condition

2. Two devices that are commonly used for short circuit protection:
   a) fuses and circuit breakers
   b) CTs & PTs
   c) Arresters and arrester counter
   d) battery and charger

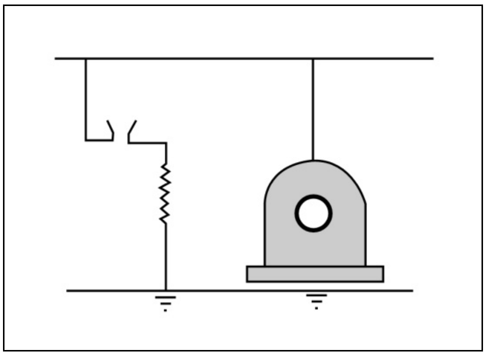
3. A _________ is a link that can be melted by heat due to over-current.
   a) fuse
   b) relay
   c) circuit breaker
   d) shunt

4. The melting of a fuse is often accompanied by a puff of smoke of vaporized metal that is called fuse……………
   a) lighting
   b) breaking
   c) igniting
   d) blowing

5. Fuses protect the circuits from ___________.
   a) over-voltage
   b) short circuit
   c) under-voltage
   d) both a & c

6. Lightning arresters protect the circuits from ___________.
   a) over current
   b) short circuit
   c) over voltage
   d) under-voltage

7. The lightning arrester type shown below is ___________.
   a) horn gap type
   b) valve type
   c) expulsion type
   d) extrusion type



8. A fuse is mainly a/ an___________.
   a) isolating device
   b) protecting device
   c) arresting device
   d) both (a) & (b)

9. Fuses are relatively ___________.
   a) expensive protective devices
   b) used for HV transmission only
   c) inexpensive protective devices
   d) used for LV transmission only

10. A fuse is an intentionally ___________ link in an electrical circuit.
    a) strong connecting
    b) weak disconnecting
    c) strong operating
    d) none of above

11. Copper loss (I^2R) is consumed in the electrical circuit as ___________.
    a) magnetic field
    b) heat energy
    c) electrostatic field
    d) light energy

12. Fuses are enclosed to ____.
    a) prevent the molten metal from flying and doing damage or fire
    b) allow the molten metal to fly in the air
    c) help to quench fire caused by the molten metal in the absence of air
    d) both b & c

Fill-in the blanks:

13. Lightning arresters are devices that protect the electrical system from ___________ and ______________________ by providing a low impedance path to ___________.

14. __________ must be installed as close as possible to the protected objects.

15. The ______________ is used in conjunction with lightning arresters for recording and monitoring of lightning discharges in the system.

TASK 3.3-1

HIGH VOLTAGE PROTECTION DEVICES

OBJECTIVE

Upon completion of this task, the participants will be able to:

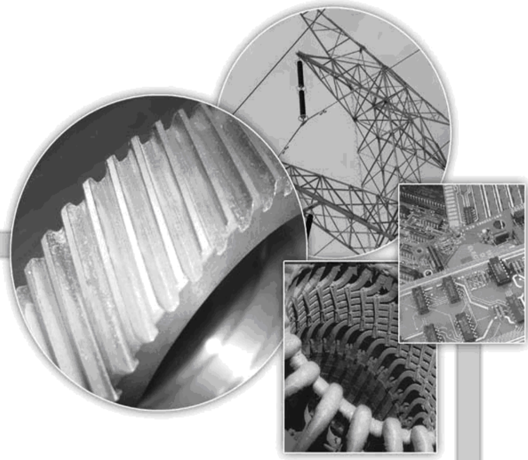
- Demonstrate the high voltage protection devices.

TOOLS, EQUIPMENT & MATERIALS

- High voltage fuses (different rates in kV).
- Surge and lightning arrestors (different types).

PROCEDURE:

1. Identify the main types of high voltage fuses.
2. Explain the cartridge type fuse.
3. Explain the primary plug fuse.
4. Identify the expulsion fuse.
5. Identify valve type arresters and explain how they work.
6. Identify valve type arresters, and explain how they work.
7. Explain the arrestor counter, and how it works.
8. Identify the metal oxide type surge arrestor.



LESSON 3.4

REACTIVE POWER COMPENSATION

LESSON 3.4
REACTIVE POWER COMPENSATION

OVERVIEW

This lesson explains the effect of line reactance and reactive power on transmission line voltage, using series reactor, shunt reactors, and shunt capacitors for compensation.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Represent the TL components and its reactance effect on line voltage regulation.
- Verify series and shunt capacitor compensation.
- Identify the function of series and shunt reactors in long transmission line.
- Use transmission line simulator to demonstrate the effect of loading on medium length TL.

Task 3.4-1: Effect of loading on medium transmission line

INTRODUCTION

Reactive power compensation is defined as the management of reactive power to improve the performance of AC power systems. The concept of VAR compensation includes wide field applications in both system and customer level PF problems, especially related to cost and quality of power.

EFFECT OF LINE REACTANCE ON LINE VOLTAGE REGULATION

An electrical transmission line, in addition to conductor resistance, always contains two more passive circuit components, series inductance and shunt capacitance. As line loading increases, the voltage drop due to current flowing through the series inductive reactance **(E_{Line} = I** x **X_L)** becomes appreciable, resulting in a receiving-end voltage considerably below the sending-end voltage. In addition, because current through an inductance is lagging, the phase angle between the sending and receiving ends of the line may reach the limit of stability considerably before the load-carrying capability of the line is reached. Fig. 3.4-1 shows a vector diagram of a transmission line where current lags the voltage. This diagram is approximate, since the inductance and capacitance of a transmission line are distributed throughout its length and an exact representation of a long line is considerably more complex than indicated. However, this figure should serve to indicate the effect of inductive reactance of a line.

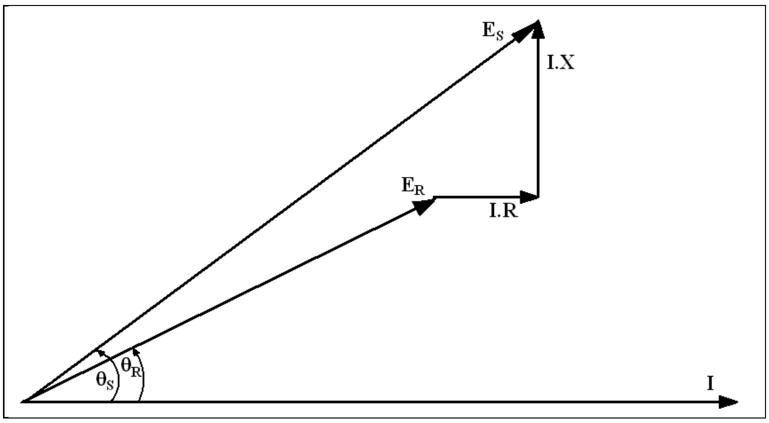


Fig. 3.4-1 Vector Diagram of Transmission Line Operating at Lagging Power Factor

The receiving-end voltage E_R is less than the sending-end voltage E_S by the vector sum of the voltage drops in the line caused by current through the line resistance and the line reactance. θ_S is the angle between the current and voltage at the sending end, and θ_R is the angle between the current and voltage at the receiving end of the line. The difference between θ_S and θ_R is the phase shift in the line. On the other hand, capacitance exists between 'conductors of a line' and between the 'conductors and ground'. When a line is lightly loaded, the capacitive charging current may exceed the load current, resulting in the line operating with a leading power factor. In such cases, the receiving-end voltage will rise and may exceed the voltage at the sending end of the line. This condition is indicated in the vector diagram shown in Fig. 3.4-2.

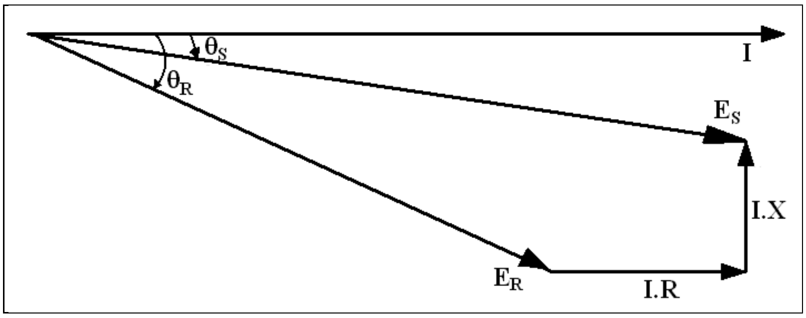


Fig. 3.4-2 Vector Diagram of Transmission Line Operating at Leading Power Factor

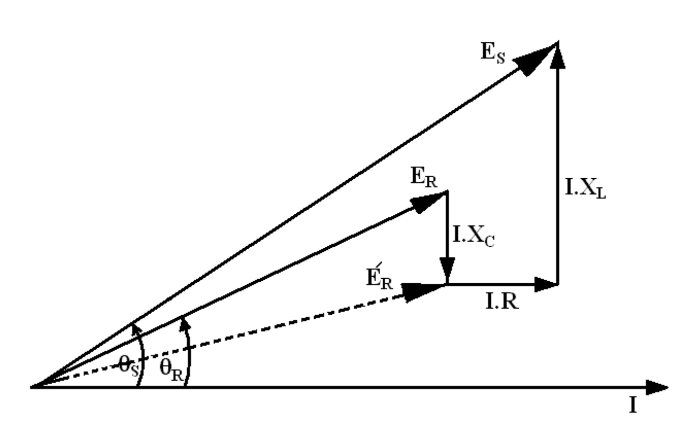
In lines with bundled conductors, the capacitances involved are greater than those in lines with single conductors, resulting in increased capacitive charging currents. Furthermore, as line voltage is increased, the capacitive charging KVAR of a line increases. For example, on a 500 kV line with two bundled conductors, approximately 2000 KVAR/mi of capacitive reactive supply is required.

If a long line is lightly loaded, its receiving-end voltage will rise above that of the sending end. If it is heavily loaded, the receiving-end voltage will drop considerably below the sending-end voltage. When the voltage rise at light loads is excessive, insulation may be overstressed or voltage-regulating equipment at the receiving-end station may go out of range, resulting in undesirable customer voltage conditions.

When a long line is heavily loaded and its receiving-end voltage drops excessively, voltage-regulating equipment may go out of range and cause customer voltage to fall below normal. In order to minimize the adverse conditions mentioned above, series capacitors and shunt reactors are used on long HV transmission lines.

REACTANCE COMPENSATION WITH SERIES CAPACITORS

When installed in series with a line, installed in a line, the voltage drop through the series capacitive reactance is proportional to the line current and the capacitive reactive drop is vectorially opposite to the drop through the line inductive reactance. The result is reduced voltage regulation at the receiving end of the line. This is shown in the vector diagram in Fig. 3.4-3.



ES: Sending end voltage

ER: Receiving end voltage

ÉR: Receiving end voltage without capacitor

Fig. 3.4-3 Approximate Vector Diagram showing Effect of Series Capacitor Compensation in Transmission Line

From Fig. 3.4-3, the receiving-end voltage **(E_R)** with series capacitor compensation is considerably higher than the voltage **(E'_R)** that would exist without the use of series capacitors. The phase shift between the sending and receiving ends of the line is reduced when series capacitors are used. In effect, the series capacitors shorten the line electrically and make it possible to carry more load without losing stability than would be without capacitors.

Series capacitors used for high-voltage line compensation are made up of groups of capacitor units similar to those used for Power Factor correction on distribution lines and connected in series-parallel. The number of units connected in series is sufficient to withstand the maximum voltage drop expected across the capacitors. The number connected in parallel is determined by the normal line currents expected. The series capacitors must operate at line voltage and they are mounted on platforms with sufficient insulation to withstand the line-to-ground voltage of the transmission line.

Series capacitor installations can be made with all the capacitors at one location, such as the midpoint of the line section or with one-half the capacitors at each end of the line. Both types of installations are in service and the location where to install capacitors based on engineering and economic considerations. Fig. 3.4-4 & Fig. 3.4-5 show a single-line schematic diagram of both types of installations.

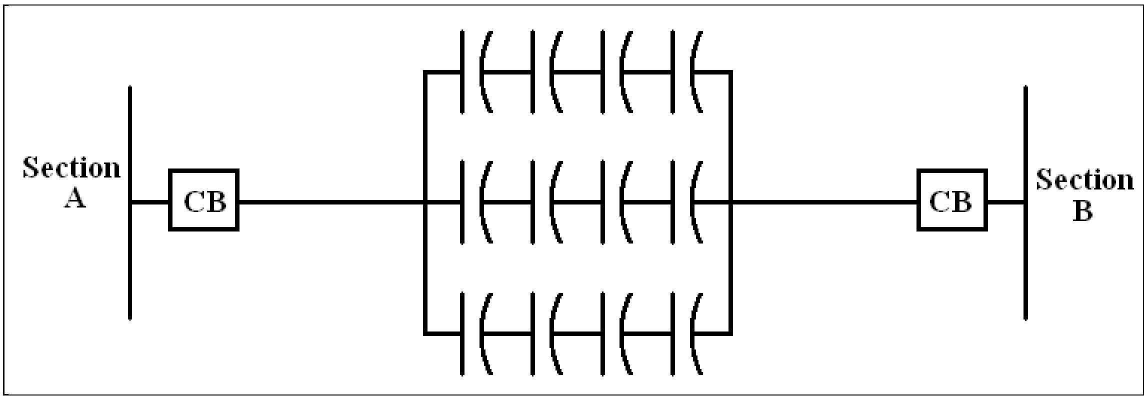


Fig. 3.4-4 Line with Series Capacitor Installed at Midpoint

Fig. 3.4-5 Line with One-Half Series Capacitor Installed at each End

Actual installation of series capacitors is always including series and parallel capacitor groups. Disconnecting, bypass, and ground devices are included at each installation.

EFFECT OF SHUNT CAPACITORS ON LINE

The power factor improves by connecting shunt capacitors with the line, as shown in Fig. 3.4-6.

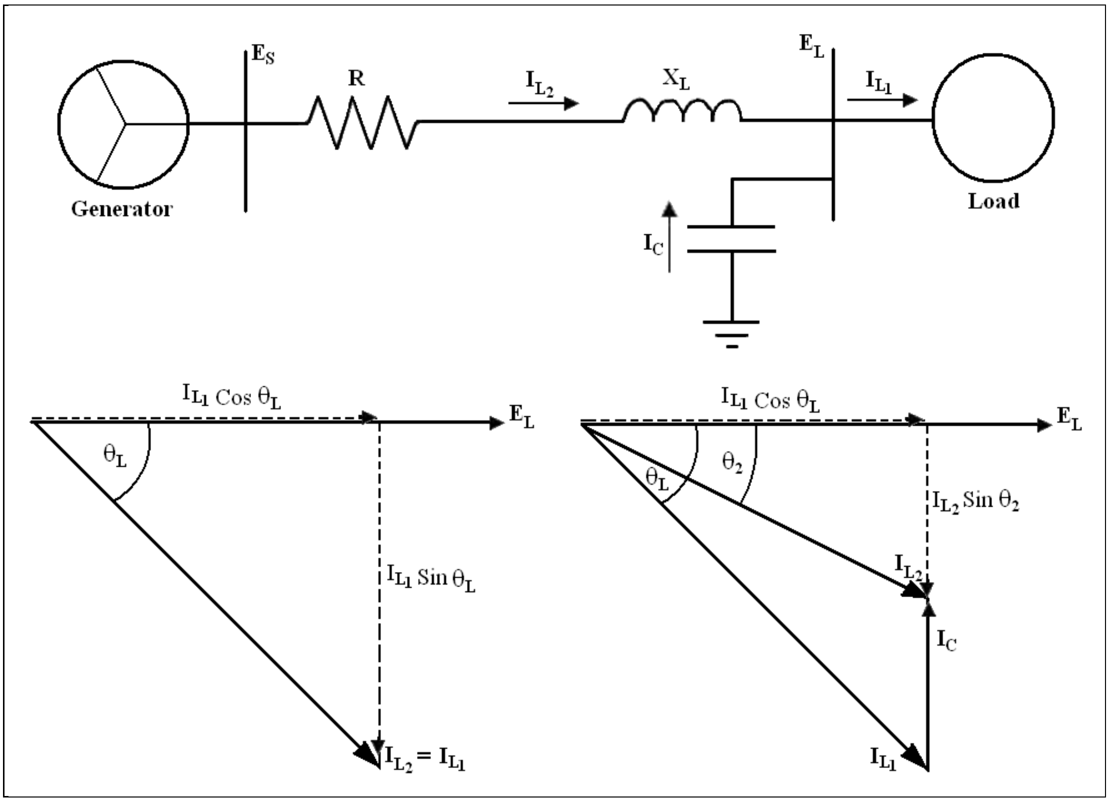


Fig. 3.4-6 Effect of Shunt Capacitors on Transmission Line

Shunt capacitors provide a source of reactive current installed closer to the load. This allows reduction of current in the system up to the point of application, resulting in higher voltage level at the load and lower line losses because transportation of a large percentage of the system's reactive load is eliminated, that permits supplying more loads with active power through the line.

LOCATION OF SHUNT CAPACITORS

As for secondary lines, shunt capacitors are installed at the location where several service drops occur or directly at the load.

Fig. 3.4-8 shows a capacitor with two terminals, a bleed resistor, and a number of capacitive elements in series.

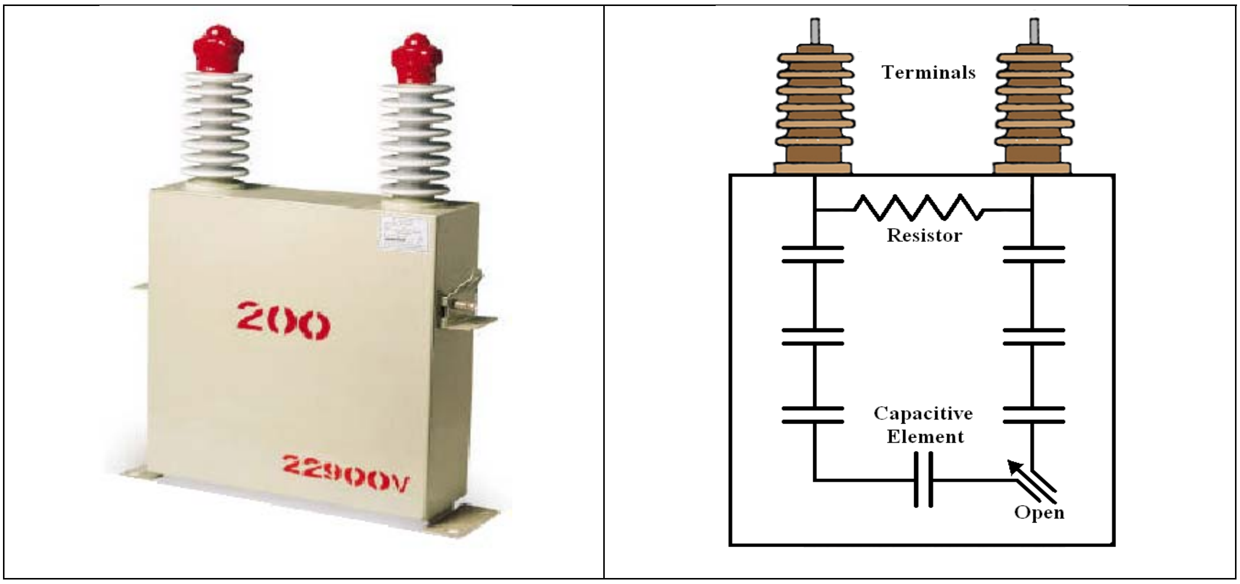


Fig. 3.4-8 Two Terminal Capacitor Bank and its assembly

COMPENSATING REACTORS

The reactors are used in electrical system as current or voltage limiting and are of generally two types:

- Series reactor
- Shunt reactor
-

SERIES REACTOR

Series reactor is non-ferrite type wound coil in which no magnetic material is present and iron core type is a coil wound around a core of iron. The oil-immersed reactor core material may be air, concrete, or wood, as shown in Fig. 3.4-9. In normal operation, the series reactor offers very low impedance in series with the line.

The function of series reactor is to create high series impedance in the circuit when fault occurrence to limit the fault current.

Fig. 3.4-9 Dry Type Air Core Series Reactor

Fig. 3.4-10a shows oil immersed reactor for current limiting in power circuit under fault condition.

Fig. 3.4-10a Series Reactor

Fig. 3.4-10b Shunt Reactor

SHUNT REACTORS

Shunt reactors (Fig. 3.4-10b) are the most compact and cost efficient means of compensating capacitive generation in long distance high-voltage power transmission

lines or extended cable systems. Under light load conditions, the capacitive charging current may cause excessive voltages at the receiving end of a long HV line. This situation is the exact opposite of that, which occurs under heavy load conditions where series capacitors are used for compensation.

In order to compensate for the voltage rise resulting from capacitive charging currents, inductive reactance (shunt reactor) is installed in parallel with distributed capacitive reactance from line to ground, as shown in Fig. 3.4-11.

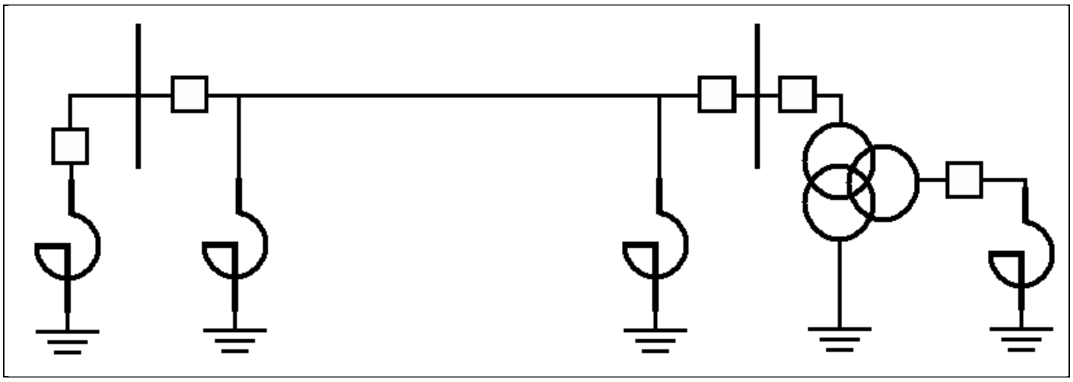


Fig. 3.4-11 Shunt Reactor Application in Power System

Such installations draw lagging current and correct for the voltage rises that occur in the lines under lightly loaded conditions. Shunt reactors are used in many transmission substations in SEC, for example in many substations at 380 kV transmission lines from Shedgum to Riyadh. Shunt reactors are named as Static VAR Compensators. In Shedgum, 380 kV Substation, the static VAR compensator includes transformer oil-filled reactor and thyristor for controlling the reactor, as shown in Fig. 3.4-13.

In some cases, the compensator is connected on the tertiary winding of an existing transformer, as shown in Fig. 3.4-11.

STATIC VAR COMPENSATION

Static VAR compensator is a bank of individually switched capacitors in conjunction with a thyristor controlled iron-core reactor. By means of power semiconductor switches, the reactor may be variably switched into the circuit, and so provide a continuously variable MVAR injection (or absorption) to the electrical network.

In this configuration, voltage control is provided by the capacitors; the thyristor-controlled reactor is to provide smooth control. Smoother control and more flexibility can be provided with thyristor-controlled capacitor switching.

The thyristors are electronically controlled. Thyristors, like all semiconductors, generate heat, and deionized water is commonly used to cool them. Chopping reactive load into the circuit in this manner injects undesirable odd-order harmonics, and so banks of high-power filters are usually provided to smooth the waveform. Since the filters themselves are capacitive, they also export MVARs to the power system.

1. 0-250 MVAR Meter
2. 0-500 kV Voltmeter
3. 0-15 kV Voltmeter
4. 0-5 KVA meter
5. Anunciator
6. TCR Control Instruments
7. Position Indicator
8. Block/Unblock Pulses
9. Emergency Switch OFF
10. Phase Selector Switch

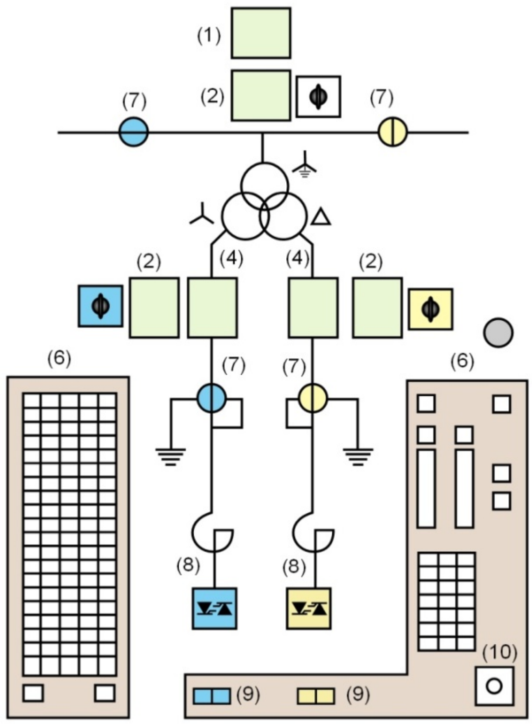


Fig. 3.4-12 Static VAR Compensator

THYRISTOR CONTROLLED REACTOR (TCR)

TCR is static VAR compensator installed in many SEC substations. The TCR is necessary for the following reasons:

A. To maintain voltage at constant level:

1. Under slowly varying conditions due to load changes.
2. To correct voltage changes caused by unexpected events.

3. To reduce voltage flicker caused by rapidly fluctuating loads.

B. To improve power system stability:

1. By supporting the voltage at key points (midpoints of long lines).
2. By helping to improve damping swing.

C. To improve power factor:

Fig. 3.4-13 shows the basis of TCR connection.

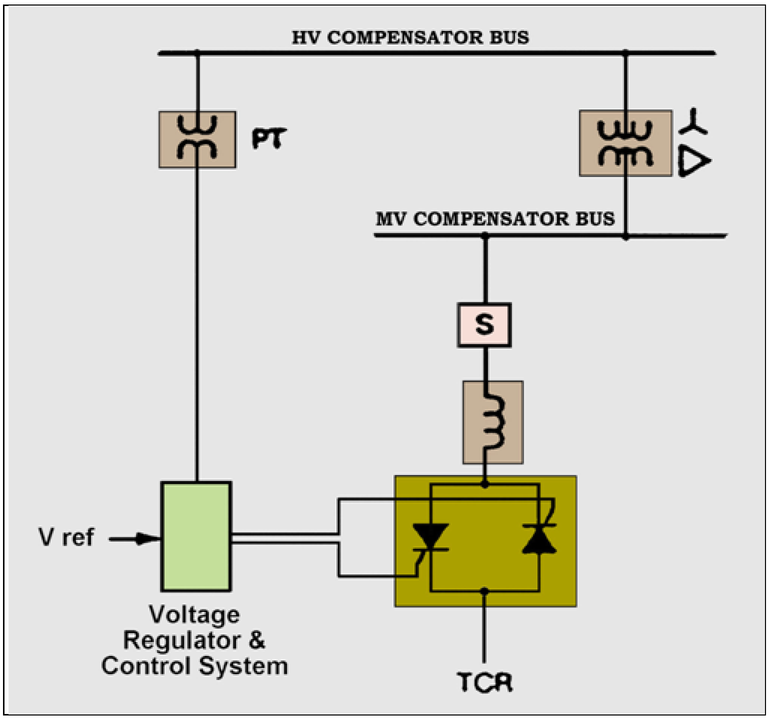


Fig. 3.4-13 Single Line Diagram of TCR Compensation

The controlling element is the thyristor controller. The two thyristors paralleled in opposite polarity conduct on alternate half cycles of the supply frequency. If the thyristors are gated precisely at the zero-crossing point of the supply voltage, full conduction results in the reactor and the current is the same as though the thyristor controller were short-circuited. The current is essentially reactive, lagging the voltage by nearly 90°.

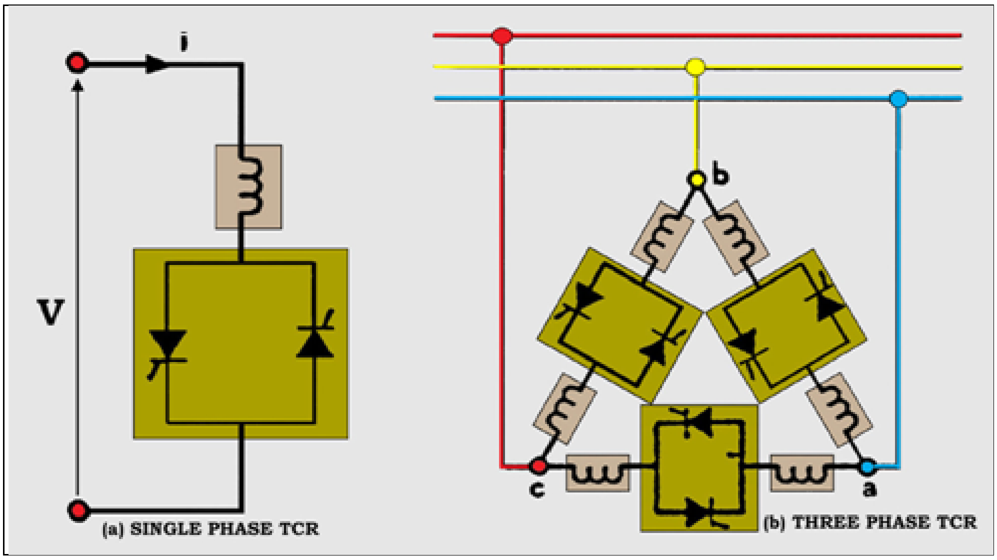


Fig. 3.4-14 1ϕ and 3ϕ TCR Compensators

The 12 pulse connection has the advantage that if one half is faulted the other may be able to continue to operate normally, as shown in Fig. 3.4-15. The 12 pulse TCR uses transformer with two secondary terminals for independent control as used in 380 kV Shedgum and Faras Substations.

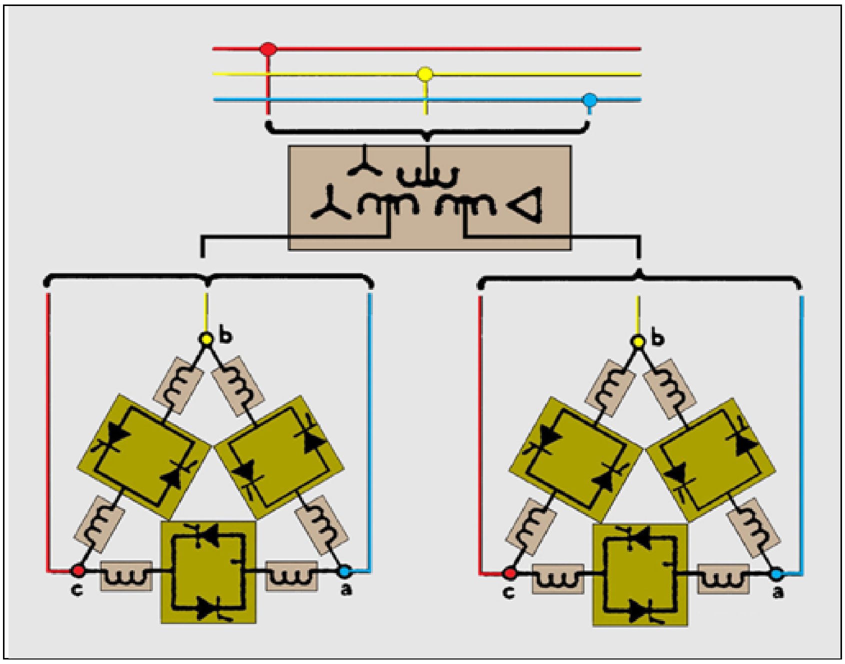


Fig. 3.4-15 12 Pulse TCR with Dual Secondary Transformer

SUMMARY

- The transmission line is represented by conductor resistance, series inductances, and shunt capacitors.
- When transmission line lightly loaded, the capacitive charge current exists with leading power factor, and receiving-end voltage higher than sending-end voltage.
- When the transmission line is loaded, the receiving-end voltage drops below the sending-end voltage, having lagging power factor without VAR compensation.
- The series capacitor installations can be made with all the capacitors at one location at the midpoint of the transmission line or with one-half the capacitors at each end of the line, based on engineering and economic considerations.
- The shunt capacitors are installed at the location where several service drops occur or directly at the load to compensate for lagging power factors.
- The reactors are used in electrical transmission system for capacitive current and voltage raise limiting and compensation.
- Shunt reactors are sometimes called Static VAR Compensators.

FORMULAE

$$\mathbf{E_S = E_R + I\,R + I\,X_L - I\,X_C}$$

Where: E_S = Sending end voltage.

E_R = Receiving end voltage.

$I\,R$ = Drop voltage on the transmission line resistance.

$I\,X_L$ = Drop voltage on the transmission line inductance.

$I\,X_C$ = Drop voltage on the transmission line capacitance.

Note:

All the equation components are vectorial values.

GLOSSARY

TL:	Transmission Line
VAR:	Reactive power measuring unit
TCR:	Thyristor Controlled Reactor
V. Ref.:	Adjustable voltage reference
Receiving-end:	Transmission line terminal at load connection
Sending-end:	Transmission line terminal at source connection
Capacitor Bank:	Group of power capacitors in one equipment
Compensating reactor:	Coil used for current or voltage limiting
SVC	Static VAR compensator used to improve power factor and voltage raise limitation

REVIEW EXERCISE

1. Identify the approximate vector diagrams of the transmission lines with lagging and leading Power Factors (PF).

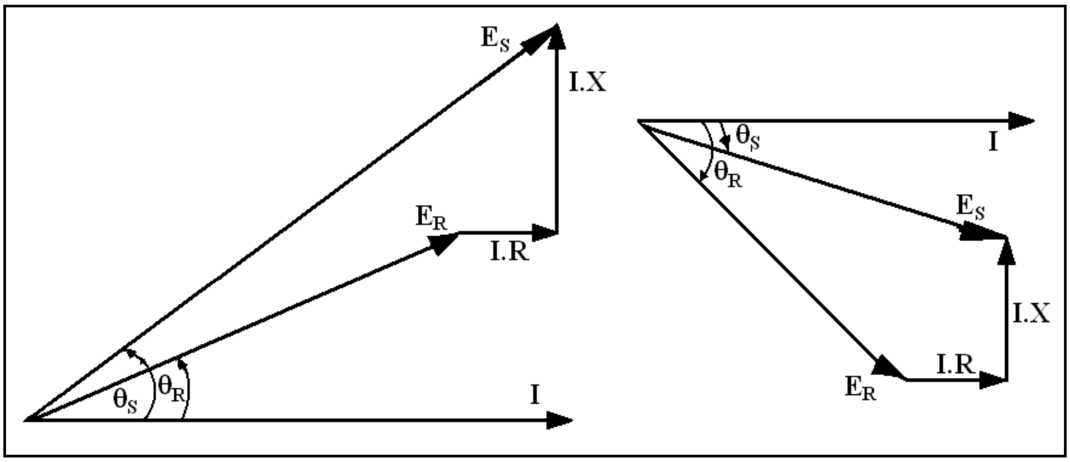


Fig. 3.4-16

Fill in the spaces:

2. In lines with bundle conductors, the capacitances involved are greater than those in lines with single conductors, resulting in ________ capacitive charging currents.

3. The phase shift between the sending and receiving ends of the line __________ when series capacitors are used.

4. The receiving-end voltage with series capacitor compensation **(E_R)** is lower than that without the use of series capacitors **($\acute{E}_R$)**.

   a) True   b) False

Answer true or false:

5. The series capacitors shorten the line electrically and make it possible to carry more load without losing stability than would be without capacitors.

   a) True   b) False

6. The series capacitors with the line improve the power factor of a transmission line by compensating for the series inductive reactance.

   a) True   b) False

7. In order to compensate for the voltage rise resulting from capacitive charging currents, shunt reactor can be installed in parallel with distributed capacitive reactance ________________________.

TASK 3.4-1

LOADING EFFECT ON MEDIUM TRANSMISSION LINE

OBJECTIVES

Upon completion of this task, the participants will be able to:

- Demonstrate the effect of loading on the medium transmission line.

TOOLS, EQUPMENT & MATERIALS

4- Transmission line simulator.
5- Resistive loads (different values).
6- AC voltmeter.

PROCEDURE

1. Receive the following from the instructor:
   a. Artificial TL, as shown in Fig. 1-1.
   b. Power source 220 VAC single-phase.

NOTE

For medium length TL, the line will demonstrate series resistive and inductive impedance and shunt capacitance between the line and the earth. So use the nominal (T) method on the Simulator.

1. Use variable resistor 1000Ω as identical load for medium length TL Do adjust I_R= 0.75A. Turn switch S_1 on into the position **(T)**.
2. Apply 240 VAC to the sending-end voltage (V_S = 240 volts).
3. Adjust the variable load (1000 Ω) to obtain I_R = 0.75 A.
4. Read the receiving-end voltage V_R.

NOTE

Due to impedance of the line (series resistance and inductive reactance and shunt capacitance), the receiving-end voltage will be less than the sending-end voltage.

5. Check the total resistance, inductance, and capacitance of the line.

NOTE

Power factor for sending end of the line is 0.96 leading.

6. Draw the vector diagram showing V_S, I_S, V_R, V_C, I_C using the given diagram as a guide.

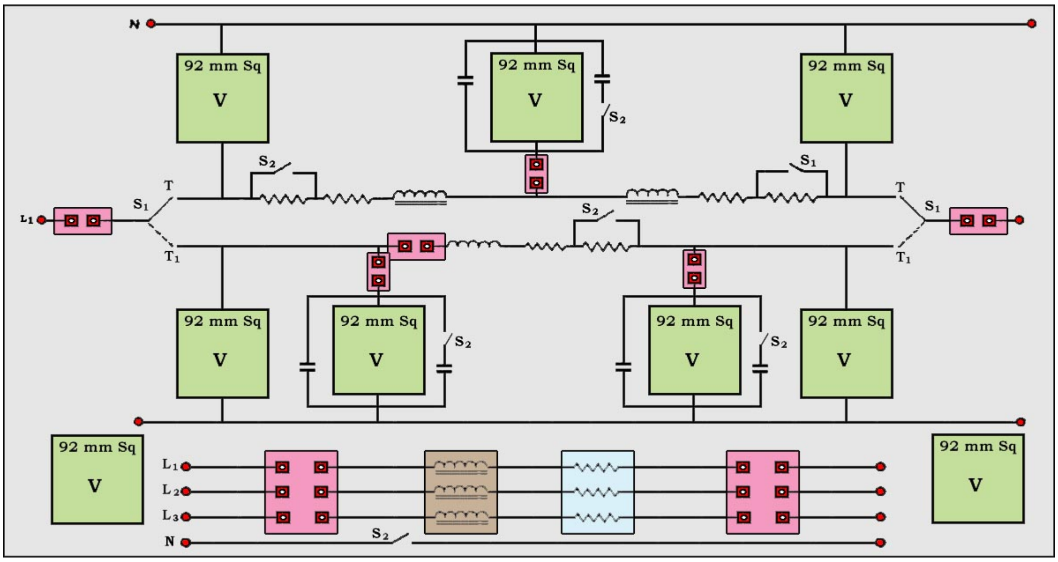


Fig. 1-1 Artificial Transmission Line

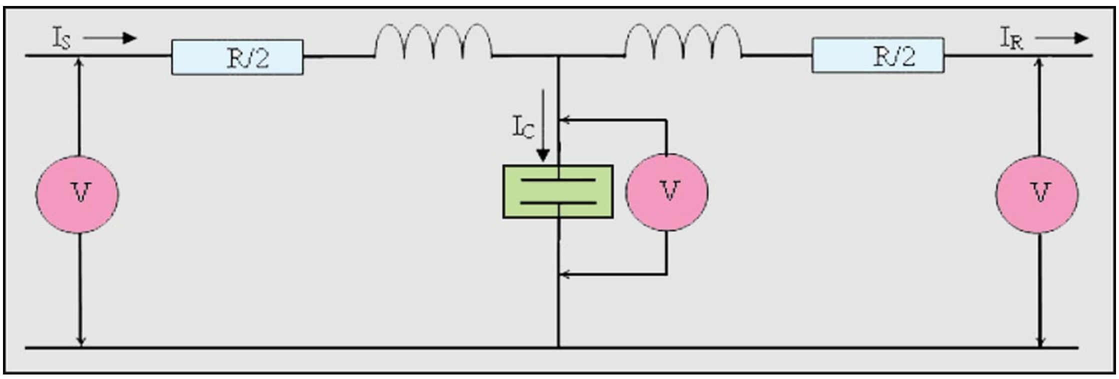


Fig. 1-2 Artificial Transmission Line (T equivalent)

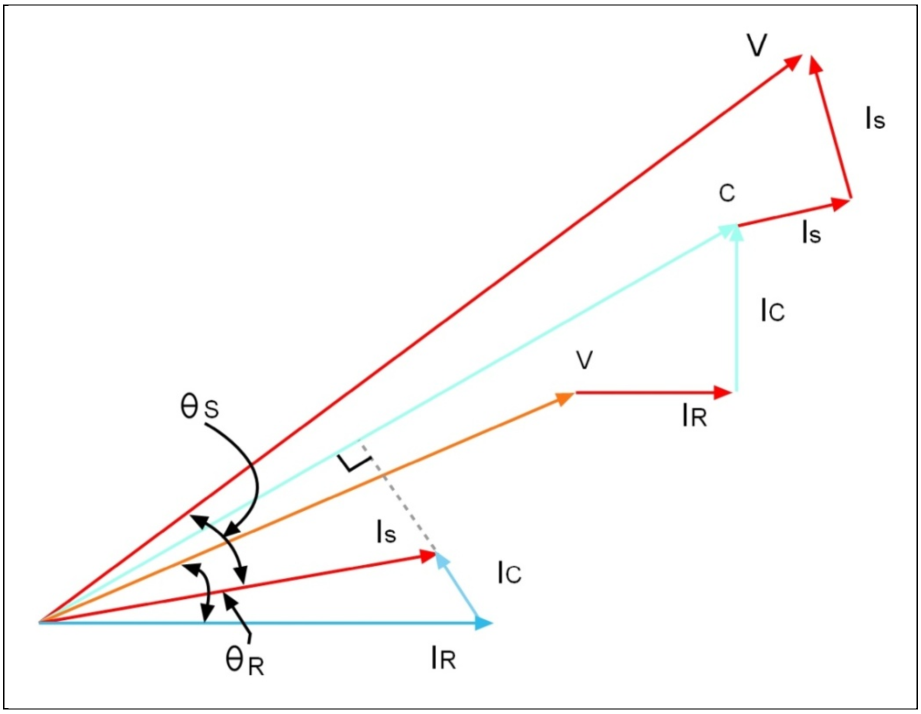
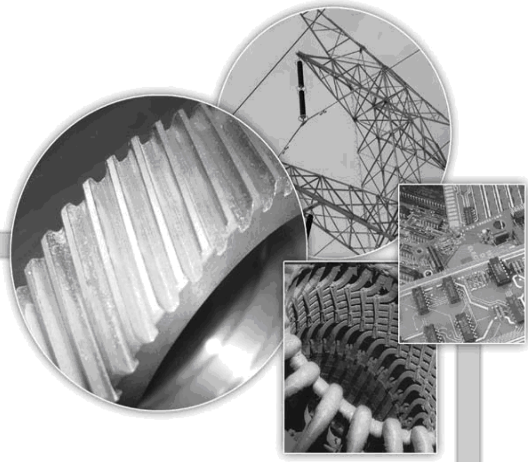


Fig. 1-3 Approximate Vector Diagram of Artificial Transmission Line



LESSON 3.5

GROUNDING SYSTEMS

LESSON 3.5
GROUNDING SYSTEMS

OVERVIEW

This lesson discusses the importance of grounding for each of human safety, power system equipment, and protection systems emphasizing on different types of grounding techniques for the power system.

OBJECTIVES

Upon completion of this lesson, trainees will be able to:

- State purposes of grounding.
- List the power system equipment that must be grounded.
- List the types of system grounds.
- List the grounding path requirements.
- Describe purposes of grounding switches and temporary grounding.

INTRODUCTION

Ground or earth is the reference point in an electrical circuit or a common return path for electric current. It has a very low resistance to the flow of current. Grounding an equipment means to connect it to the earth so that the circuit or equipment is at the same zero potential.

Electrical circuits may be connected to ground (earth) for several reasons. In mains powered equipment, exposed metal parts are connected to ground to prevent contact with a dangerous voltage if electrical insulation fails. Connections to ground limit the build-up of static electricity when handling flammable products or when repairing electronic devices. In some power transmission circuits, the earth itself can be used as one conductor of the circuit, saving the cost of installing a separate return conductor.

For measurement purposes, the Earth serves as a very good constant zero potential reference against which other potentials measurable. An electrical ground system should have an appropriate current-carrying capability in order to serve as an adequate zero-voltage reference level. In electronic circuit theory, a "ground" is usually idealized as an infinite source or sinks for charge, which can absorb an unlimited amount of current without changing its potential. Where a ground connection has a significant resistance, the approximation of zero potential is no longer valid. Stray voltages or earth potential rise will occur, which may create noise in signals or if large enough to be an electric shock hazard.

PURPOSES OF GROUNDING

Grounding systems serve three main functions:

- Maximize personnel safety, that is, minimize danger to personnel during electrical fault conditions by equalizing potentials.
- Provide low-resistance path to ground allowing sufficient current to flow and operate overcurrent protective devices and clear faults.
- Provide solid connections to earth to dissipate lightning surges and static charges.

GROUND DEFINITIONS

Ground Bus:	A bus used to connect a number of grounding conductors to one or more grounding electrodes.
Ground Current:	Any current flowing into the earth.
Grounded System:	A system of conductors in which at least one conductor or point (usually in the middle wire or neutral point of transformer or generator windings) is intentionally grounded either solidly or through a current-limiting device.
Grounding Switch:	A form of switch by means of which a circuit or piece of apparatus may be connected to ground.
Grounding Transformer:	A transformer intended primarily for developing a neutral point for grounding purpose.
Grounding Electrode:	The conductor embedded in the earth, used for maintaining ground potential on conductors connected to it and for dissipating the earth current.
Grounding Electrode Resistance:	The resistance of the grounding electrode to earth.

TOOLS AND EQUIPMENT THAT MUST BE GROUNDED

- Hand tools working near energized lines
- Lightning arrester
- Voltage transformer
- Transformer tank and platform
- Guy wire
- Capacitor rack
- Current transformer secondary
- Hand-operated switchgear

- Metering equipment
- Switchbox
- Cable Sheath
- Virtually everything that is metal except energized parts.

Fig. 3.5-1 shows typical system connections and solid grounding or through resistance.

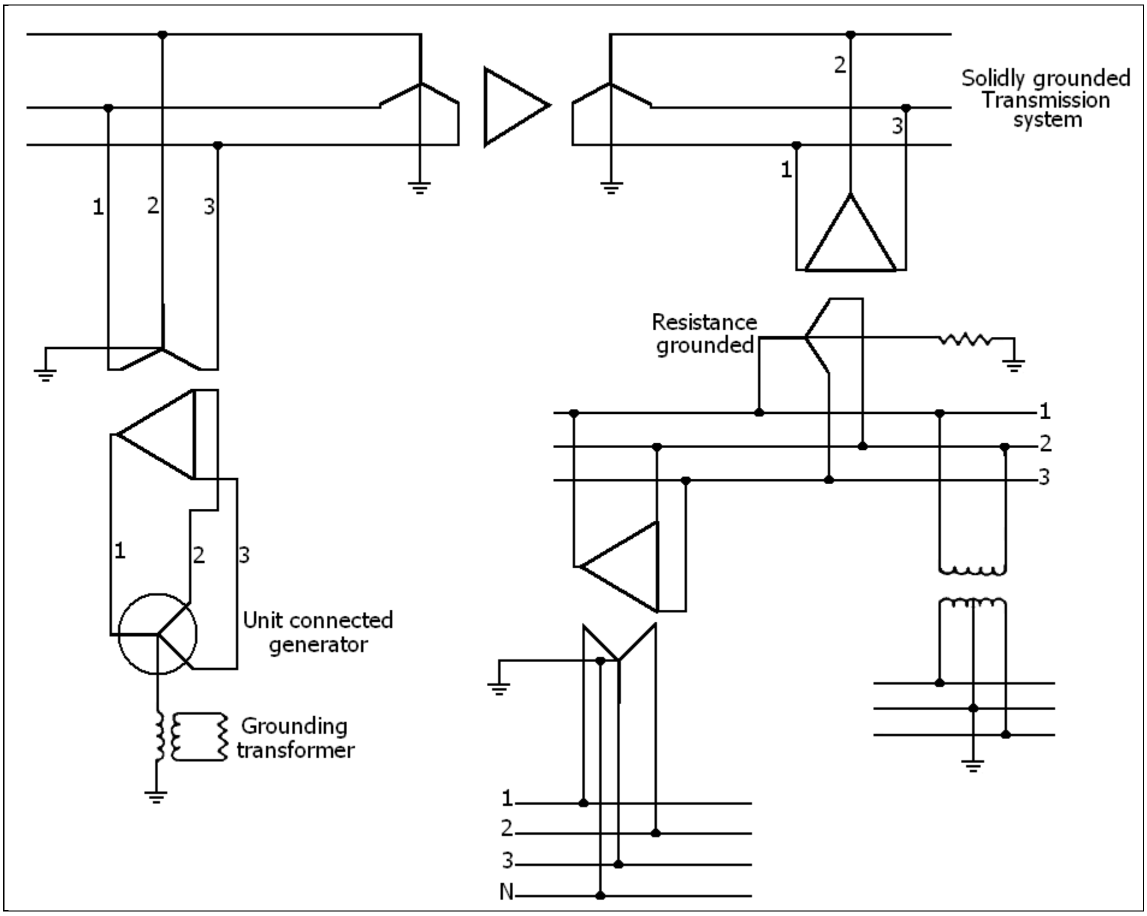


Fig. 3.5-1 Typical System Connections and Groundings

GROUND WIRE OF OVER HEAD LINE

A conductor having grounding connections at intervals, that is suspended usually above but not necessary over the line conductor to provide a degree of protection against lightning discharges. The ground wire of an overhead line is not a part of any

electrical circuit, but instead is connected to the earth at frequent intervals at least every fifth pole. On steal tower lines, it is grounded to each tower, by means of the metal clamp with which it is fastened.

TYPES OF GROUNDS

1. **Interior Wiring System Ground**
   This is a ground connection to one of the current carrying conductors of an interior wiring system.

2. **Equipment Ground**
   This is a ground connection to non-current carrying metal parts of a wiring installation or of electrical equipment or both.

3. **Neutral Ground**
   This is an intentional ground applied to the conductor or neutral point of a circuit, transformer, machine apparatus, or system.

METHODS OF GROUNDING

(a) Solid Method

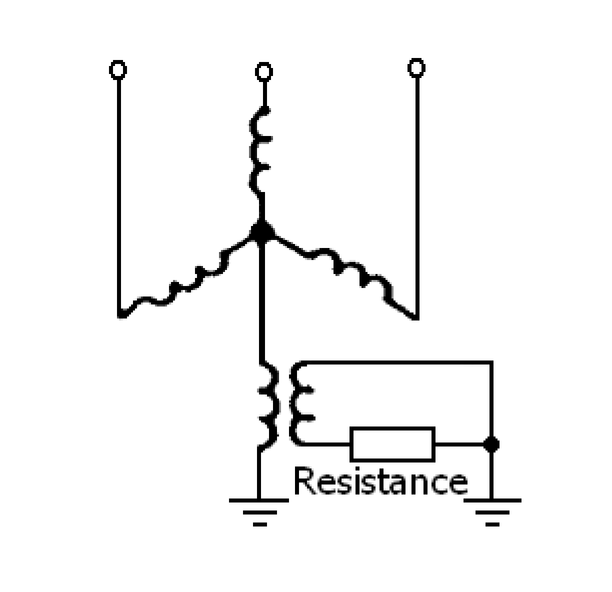
The neutral point is directly connected to ground, without including any external impedance. This method is useful when earth resistance is high.

(b) Impedance Method

The neutral point is connected to ground through impedance. This method is useful when earth resistance is low to limit earth fault current.
Grounding of the transformer neutral is shown in Fig. 3.5-2, which shows:

- High resistance grounding through transformer

- Low resistance grounding through grounding resistor



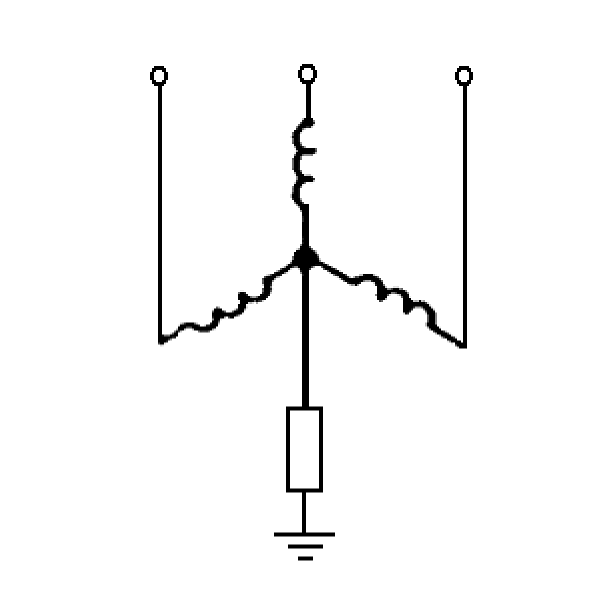


Fig. 3.5-2a High Resistance Grounding   Fig. 3.5-2b Low Resistance Grounding

(c) Zig-Zag (interconnected star) Transformer Method

Zig-Zag transformer is a special purpose transformer, it has it forms an earth reference point for an ungrounded electrical system.

The winding of each phase is divided into two halves. The first three halves of the three phases are connected in star, the terminals of these first halves is connected with the other three halves contrarily wise (cross linked), e.g. R_2 to S_1, S_2 to T_1 and T2 to R_1. In such case the output phase terminals of the Zeg-Zag transformer will be R from R_2, S from S_2 and T from T_2 as shown in Fig. 3.5-3. Thus, half of each phase voltage is added vectorial with a half of another phase voltage.

If one phase, or more, faults to earth, the voltage applied to each phase of the transformer is no longer in balance. That is, fluxes in the windings no longer oppose. Zero sequence (earth fault) current exists between the transformer neutral and the faulty phase. Hence, the purpose of a zig-zag transformer is to provide a return path for earth faults on delta-connected systems. With negligible current in the neutral under normal conditions, engineers typically elect to undersize the transformer. A

short time rating is applied (i.e., the transformer can only carry full rated current for, say, 60 s).

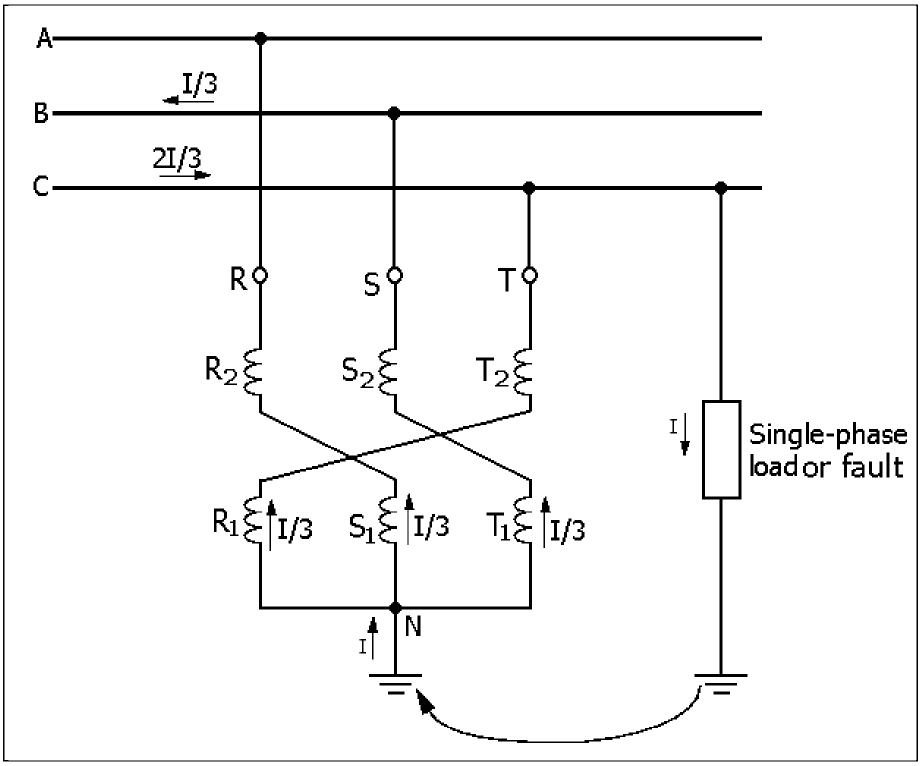


Fig. 3.5-3 Zig-Zag Transformer Grounding Connection

GROUNDING PATH REQUIREMENTS

"Effective grounding path," from circuits, equipment and conductor enclosures shall:

1. be permanent and continuous
2. have the capacity to safely conduct any fault current
3. have sufficiently low impedance to limit the voltage to ground and facilitate operation of the circuit protective devices

In general, grounding system connectors have the following requirements:

1. Must have negligible resistance
2. Must not deteriorate with age
3. Must be able to withstand repeated faults.

SYSTEM GROUND

Circuits are grounded to avoid potentially and dangerous differences in potential between two conducting surfaces. They also limit the voltage on the circuit that might otherwise occur through exposure to other voltage. The voltages are confined and made safe with grounds. A transformer circuit for a building service is shown in Fig. 3.5-4.

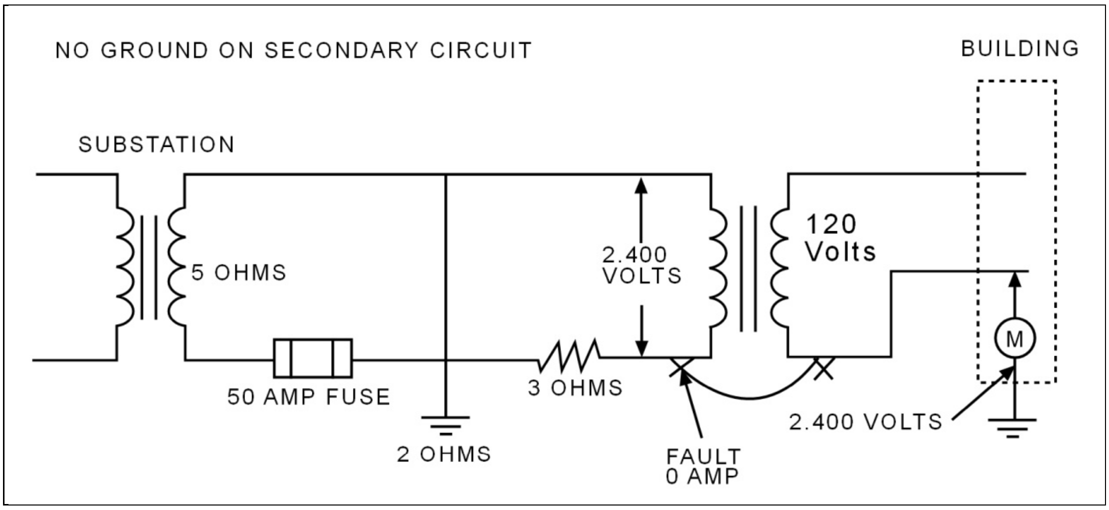


Fig. 3.5-4 Low Resistance Grounding through Grounding Resistor

In Fig. 3.5-4, assume a fault occurs, as shown, between the primary and secondary sides of the building transformer. Since there is no secondary ground, there is no fault current and the secondary system rises to the voltage of the primary system (2,400 Volts). A very dangerous situation!

When two 10 Ohms grounds are added to the circuit as shown in Fig. 3.5-5 protection is provided as shown.

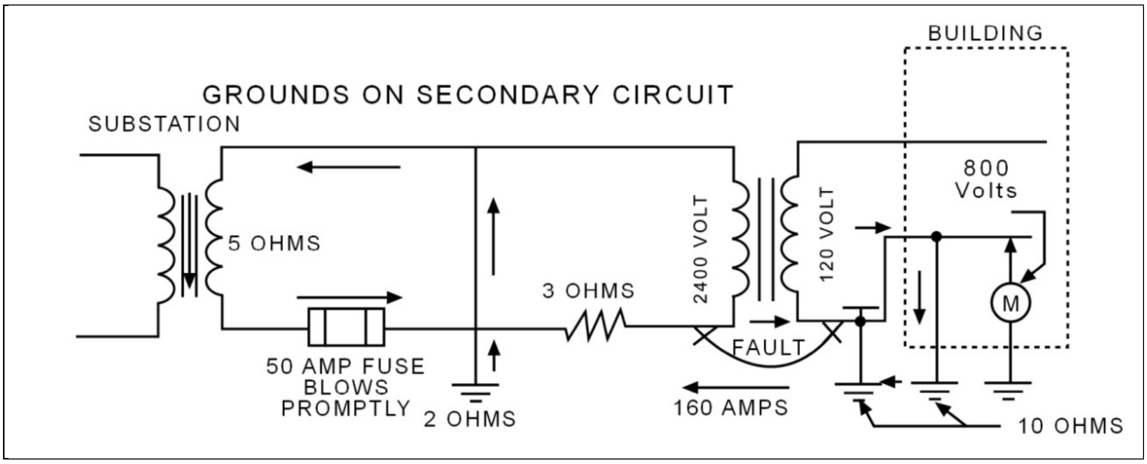


Fig. 3.5-5 Transformer Circuit with Grounds

The two-10Ω grounds in parallel become 5 Ohm ground on the neutral of the system. Adding the impedance of the distributing circuit and the transformer, there are three Ohms in the line, five Ohms in the transformer, two Ohms on the grounded side of the 2,400 Volt feeder and five Ohms in the neutral ground of the 120 Volt system, for a total of 15 Ohms for a fault current of 2,400 divided by 15, = **160 Amps**.

One hundred sixty Amperes and five Ohms for the two 10 Ohm grounds in parallel give a voltage of 800 Volts. The 160 Amp fault current promptly blows the 50 Amp fuse in the feeder. Instead of 2,400 Volts, the voltage is down to 800 Volts and exists only for the time it takes the 50 Amp fuse to blow.

Isc = Vs/Rsc Where Rsc = Total circuit resistance during short circuit

GROUND SWITCHES

When high-voltage equipment is to be discharged and grounded, it is done by a special ground switch or approved device to make ground connection. Where this is not possible, the high-voltage equipment may be discharged by a working ground lead applied by an approved device.

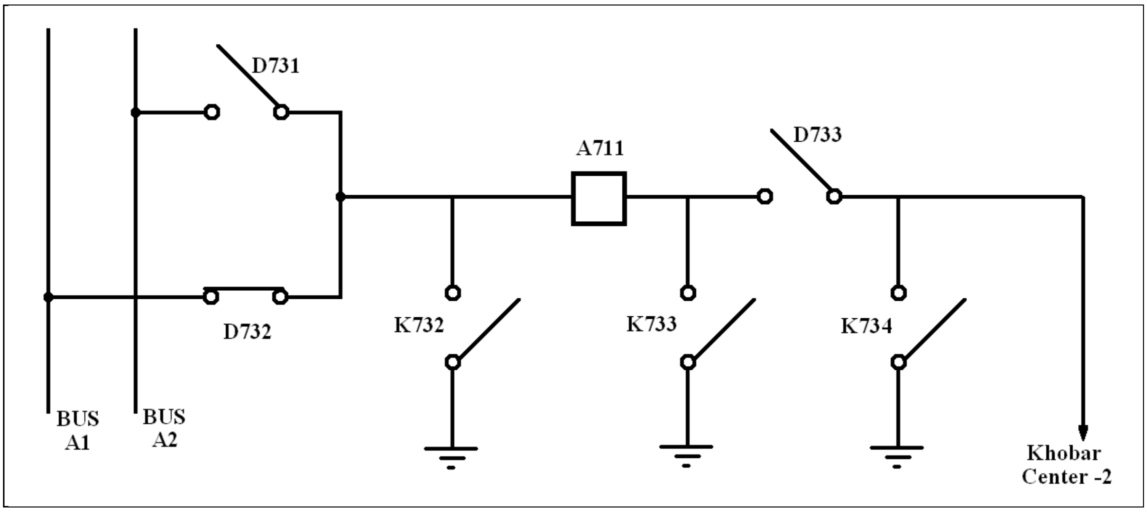


Fig. 3.5-6 Location of Disconnecting and Ground Switches

No high-voltage ground switch will be closed to the transmission or distribution system unless it is part of an approved switching operation and is approved by the Power Dispatcher or after the switching equipment has been approved by the operation personnel.

FACTORS INFLUENCING REQUIREMENTS FOR A GOOD GROUNDING SYSTEM

The following requirements must be considered in grounding system:

1. Limiting under fault conditions, electrical system voltages to specified values to earth. Use of a suitable grounding system can do this by maintaining some point in the circuit at earth potential. This will serve to protect from any system fault to ground to be quickly isolated, provide a relatively stable system with a minimum of transient over voltages, and limit the system-to-ground or system-to-frame voltage to values safe for personnel.
2. Proper grounding of metallic enclosures and supporting structures that are part of the electrical system and may be contacted by personnel.
3. Protection against static electricity from friction.
4. Protection against direct lightning strokes.
5. Protection against induced lightning voltages.

6. Providing proper ground for electrical process control and communication circuits.

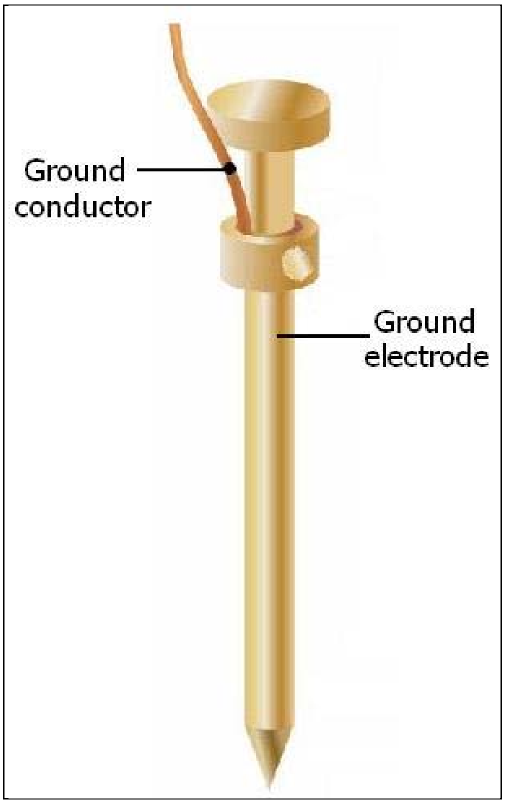


Fig. 3.5-7 Ground Electrode

GROUND ELECTRODE RESISTANCE

The National Electrical Code states that a single electrode with a resistance to ground greater than 25 Ohms shall be augmented by one additional electrode in parallel. The single-electrode grounds must be tested when installed.

TEMPORARY GROUND

Temporary ground must be applied to bus bars or transmission lines to protect the maintenance men during maintenance or repairing the equipment. The grounding cables should be of sufficient size to carry enough current to trip out the over current

protective device of the line. They should not burn out like fuse. Fig. 3.5-8 shows temporary ground clamp tools.

Fig. 3.5-8 Temporary Clamp Grounding Tools

Fig. 3.5-8 shows temporary ground stick for high voltage substation.

Fig. 3.5-9 Temporary Grounding during Maintenance

ATTACHING TEMPORARY GROUND

The procedure in applying grounding cables is to start at the earth and work toward the line. The connection at the ground or earth should be made first. This is allowed

by making the connection to the line. When the grounds are removed, the reverse order is followed. The line connection is broken first and then the ground connection.

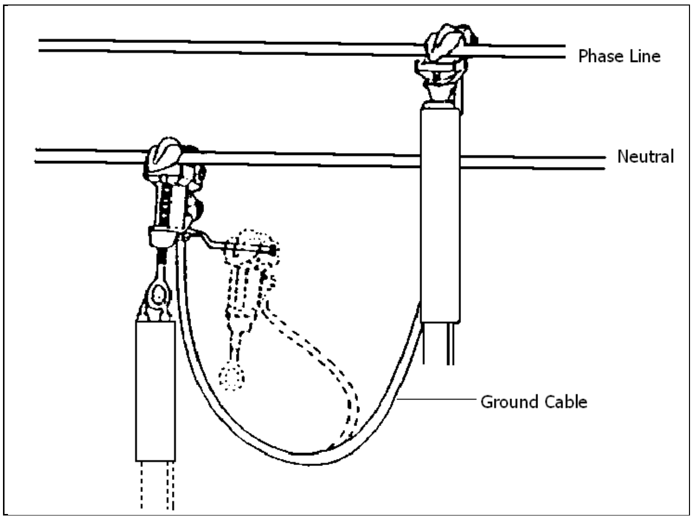


Fig. 3.5-10 Temporary Grounds

TEMPORARY GROUNDING – INDOOR GROUNDING AND TEST DEVICE

The grounding and test device or grounding cart or buggy provide a convenient means of grounding the cables or the bus in order to safeguard personnel who may be working on the cables or equipment, as shown in Fig. 3.5-11. This device, which is very much like an ordinary breaker (switch), can also be used for applying power for high potential tests or for fault location and to measure insulation resistance. By using potential transformers, it can be used for phasing out cables. The three studs of the device are similar to those of the circuit breaker. Two studs are mounted on a removable plate, which can be placed in either of the two positions, for the bus or for the line side. To indicate the proper placement of the studs on the device, each position is marked "**Line**" or "**Bus**."

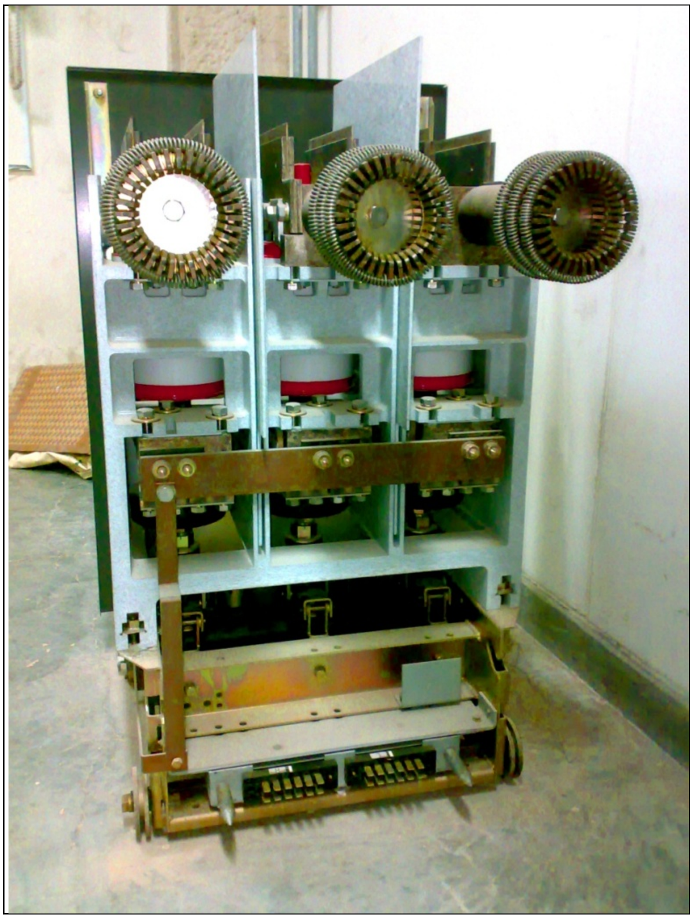


Fig. 3.5-11 Temporary Grounding Car

SUMMARY

- Grounding for the power system means connection between equipment and ground with very low resistance.
- Grounding is very important for human safety and protection of power system equipment.
- The four types of groundings are:

    - Interior Wiring System Ground
    - Equipment Ground
    - Service Ground
    - Neutral Ground

- No high-voltage ground switch will be closed to the transmission or distribution system unless approved by the Power Dispatcher.
- The National Electrical Code **(NEC)** states that a single electrode with a resistance to ground greater than 25 Ohms shall be augmented (added) by one additional electrode in parallel.
- The procedure in applying temporary grounding cables is to start at the earth and work toward the line where the connection at the ground or earth should be made first and then to the line.
- Earthing switches are used to ground power system equipment during maintenance.

FORMULAE

$I_{SC} = V_S / R_{SC}$

Where

I_{SC}: Short circuit current

V_S: Supply voltage

R_{SC}: Total circuit resistance during short circuit

GLOSSARY

NEC:	National Electrical Code
Ground switch:	A switch used to ground equipment during maintenance
Isolated system:	Equipment is not connected to the ground
Grounding electrode:	Metal stick hammered in the earth and connected to the equipment
Solidly ground:	Directly connected to ground
Impedance ground:	Connection to ground through impedance
Leakage current:	Current passes through metal body of equipment due to weakness of insulation

REVIEW EXERCISE

1. List four main functions of Grounding systems:
   a)
   b)
   c)
   d)

2. List the two methods of grounding:
   a) b)

3. The Effective grounding requires that the ground path from circuits, equipment and conductor enclosures shall have sufficiently _____ impedance to limit the voltage to ground and facilitate operation of the circuit protective devices.

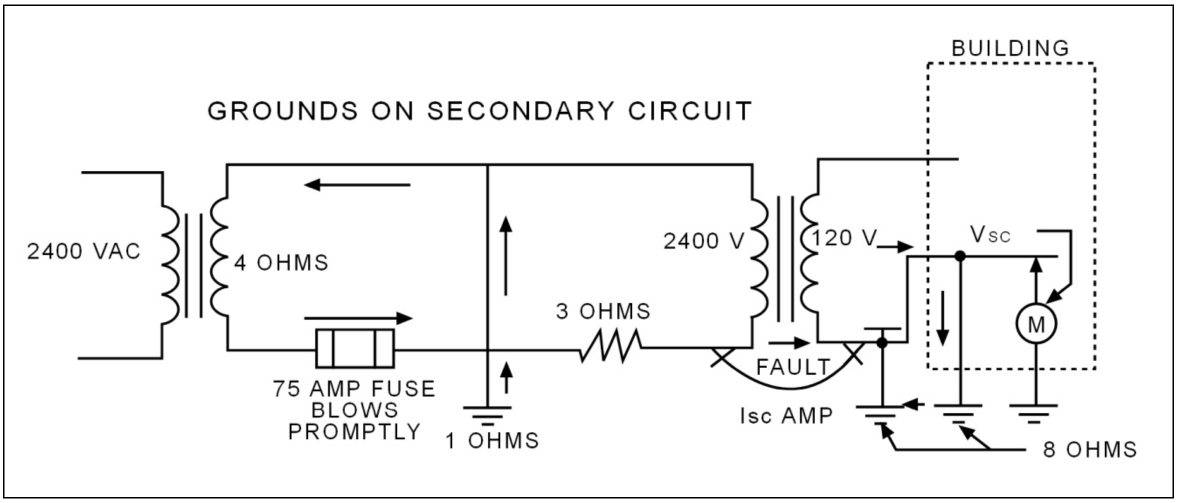


Fig. 3.5-12 Transformer Circuit with Grounds

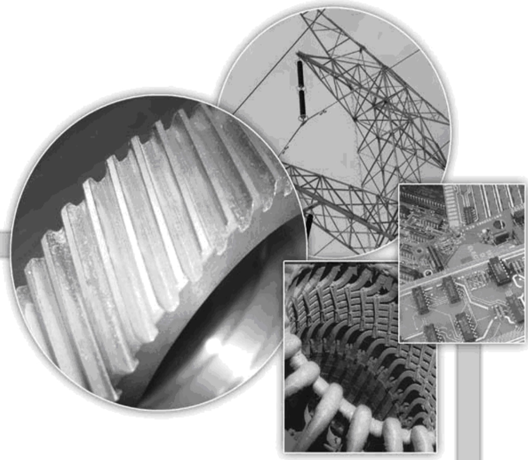
4. Given Fig. 3.5-12, assume a fault occurs, as shown, between the primary and secondary sides of the building transformer. With a fault shorting primary and secondary, the total ground resistance in the circuit is _____Ω.
   a) 8 b) 4
   c) 12 d) 15

5. Given Fig. 3.5-12, assume a fault occurs, as shown, between the primary and secondary sides of the building transformer. With the fault shorting primary and secondary, the short circuit current (I_{SC}) in the system will be _____A.
   a) 150 b) 200
   c) 120 d) 300

6. Given Fig. 3.5-12, assume a fault occurs between the primary and secondary sides of the building transformer. With the fault shorting primary and secondary, the voltage at the 120 Volt secondary due to fault will be _____V.
   a) 800 b) 2400
   c) 120 d) 1600

7. Temporary ground must be applied to bus bars or transmission lines to protect the ______________________ during maintenance or repairing the equipment.

8. When the temporary grounds are removed, the line connection is broken first and then the ground connection.
   a) True b) False



LESSON 3.6

POWER SUPPLY AND BATTERY CHARGERS

LESSON 3.6
POWER SUPPLY AND BATTERY CHARGERS

OVERVIEW

The lesson discusses the importance of power supplies used for protective equipment and control systems. In addition, it discusses the difference between battery charger types, calibration, and its basic circuits to offer the DC required for the power system.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Describe a rectifier circuit for three-phase rectification.
- State calibration and adjustment procedures for a battery charger.
- Describe the routine maintenance and inspection points for a battery charger.
- Describe a system for power supply in a substation.

INTRODUCTION

DC supply is very important in a power station, especially to operate alarms, communications, protection, and control. Group of chargeable batteries exist in a battery room, always charged by battery charger. Battery charger receives AC current and converts it to DC for charging batteries. DC supply is available in 110VDC or 220VDC.

Three-phase rectifier circuit is the main basic circuit in the battery charger to convert AC to DC. Rectifier circuits may be half wave or full wave mostly employing Silicon Controlled Rectifier (Thyristor) devices. Some general purpose applications may use uncontrolled diode rectifier circuits for DC supply.

The basic arrangement for three-phase rectifier is shown in Fig. 3.6-1.

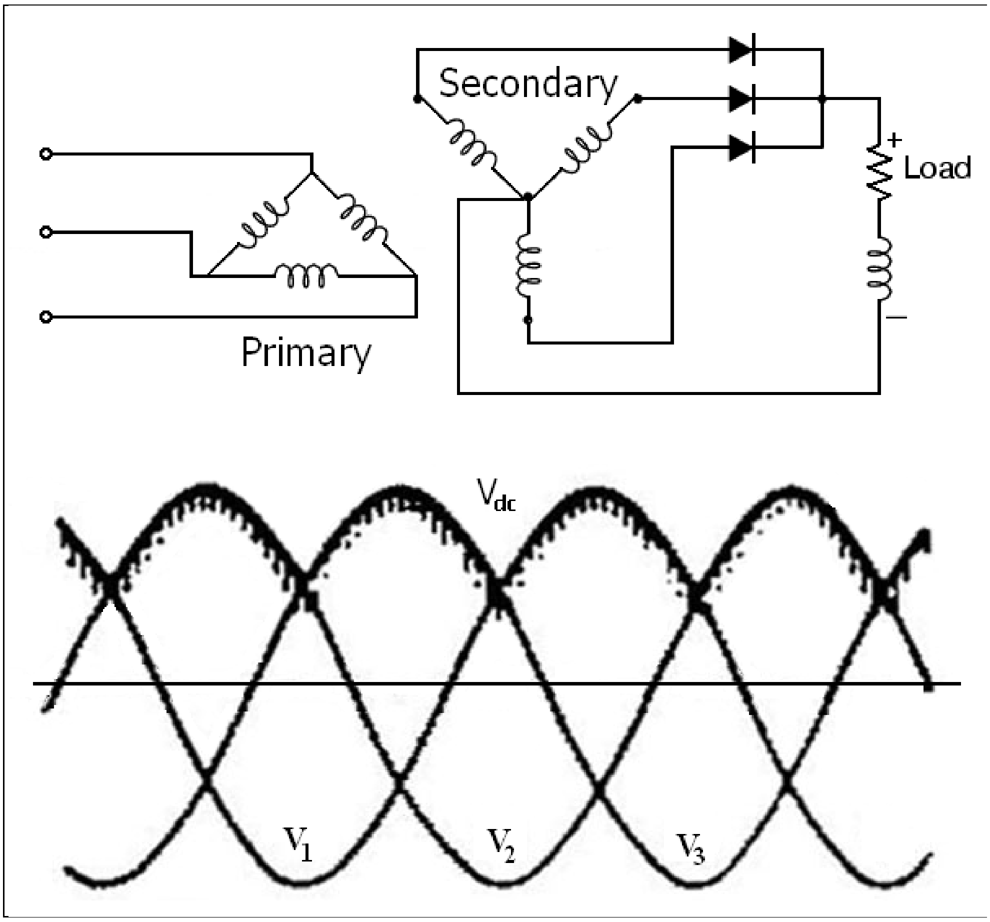


Fig. 3.6-1 Three-Phase Half wave Uncontrolled Rectifier

Fig. 3.6-2 shows three-phase Full-Wave bridge uncontrolled rectifier and the output waveform.

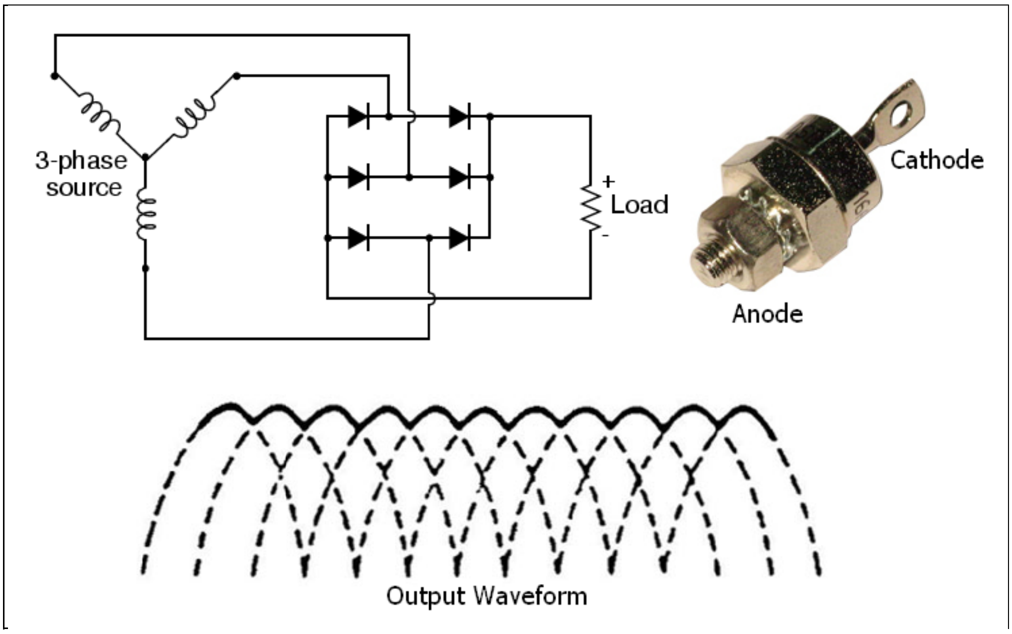


Fig. 3.6-2 Three-Phase Full-Wave Uncontrolled Bridge Rectifier

The complete rectifier circuit must contain smoothing capacitor circuit, voltage regulator circuit. In addition, a protective system must be located with the rectifier circuit. The controlled rectifier circuits have pulse circuit to trigger the rectifier devices to control the output DC voltage.

It is important to control the output DC voltage in order to control the charging process to keep the batteries in safe operation. Fig. 3.6-3 shows three-phase full wave fully controlled bridge rectifier using thyristors.

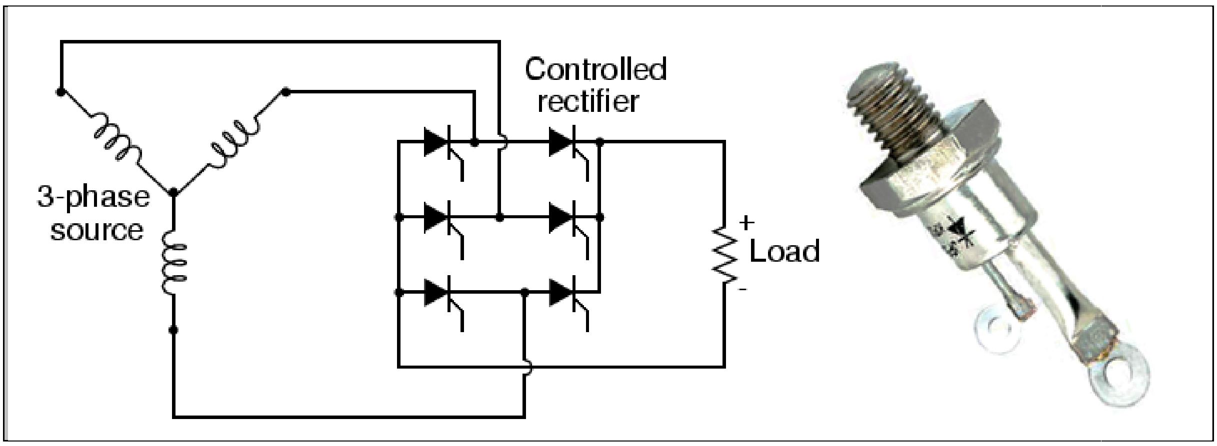


Fig. 3.6-3 Three-Phase Full-Wave Controlled Bridge Rectifier using Thyristor

STATION BATTERIES

In each substation, there is a battery room with two sets (banks) of batteries connected in series. The batteries 120 or 220VDC connected to the charger most of the time supply the required DC for different applications, such as switchgear closing and tripping functions, protection circuits and indication lights on the switchgear panels. There are two chargers but only one is connected to the batteries, while the other charger is on standby. The power is transformed and rectified internally in the charger. Fig. 3.6-4 shows the battery room containing the connecting batteries in groups.

Fig. 3.6-4 125VDC Battery Groups

SOLID-STATE CHARGER

Solid-state charger is a type of battery charger, which uses Full-Wave fully controlled bridge rectifier, as shown in Fig. 3.6-3. The charger circuit contains AC and DC breakers, DC voltmeter and ammeter, float or equalizer selector switch and potentiometer to adjust the float and equalize set-point manually, or digitally. The complete battery charger cabinet contains the low pass filter, measuring instruments, and means of DC protection system, as shown in Fig. 3.6-5.

Some battery chargers offer different voltage values, and some battery chargers have programmable system for automatic charging process without human interface.

Fig. 3.6-5 Solid State Charger in Substation

CHARGER INSPECTION AND ADJUSTMENT

All types of chargers require periodic inspection and adjustment in service. The inspection and adjustment process is an essential part of keeping batteries and chargers operating efficiently. For instance, float charged batteries must be constantly kept in good condition. In case of emergency, periodic inspection and adjustment of a charger assures that a float-charged battery is ready for use to trip circuit breakers and supply emergency light.

INSPECTION AND CLEANING

A charger should first be inspected for any signs of excessive heat. The outside of the charger can be felt to determine if the charger is too hot. Excessive heat can indicate possible damage to thyristors or diodes. The voltmeter and the ammeter on the outside of the charger, as shown in Fig. 3.6-5, should be checked to make sure that voltage

and current are within normal operating ranges and any discrepancies are noted. For example, if a voltmeter on a charger connected to a 48 cells station acid battery reads 150 Volts, the reading is probably outside the normal operating range. Likewise, if an ammeter on a charger connected to the same station battery reads maximum scale reading outside the normal operating range, the charger meters will need recalibration or replacement.

CALIBRATION OF METERS

A portable standard voltmeter precisely calibrated and tested for accuracy is used to calibrate the charger voltmeter. If the reading across the panel voltmeter terminals is less than the used voltage, there may be an undesirable voltage drop in the control circuitry of the charger. If both readings agree, the panel voltmeter is adjusted to match the voltage reading by turning its zero adjustment screw. The interior of the charger is examined for any obvious problems. Examples of obvious problems include loose or damaged wires and/or components.

CLEANING THE CHARGER

The interior of the charger is cleaned. All dust-collecting surfaces inside the charger are brushed, vacuumed, or blown clean. When cleaning the inside of an energized charger, insulated tools should be used. Tools with metal nozzles should be avoided and the metal portion of brushes should be taped. In cleaning the charger, special attention is paid to heat-radiating surfaces where dust and dirt collected on these surfaces decrease their heat dissipating capabilities. If this condition continues, overheating could damage the rectifier diodes.

ADJUSTMENTS

As a charger is used, periodic adjustments are necessary. Typical adjustment procedures vary with the type of charger, the manufacturer and plant procedures.

However, some adjustment procedures are common to all types of rectifier and solid-state chargers.

Frequent adjustments of Potentiometers necessary as a charger stays in service for long period. Typically, a screwdriver is used to adjust the float and equalize set points on the charger control panel. These adjustments assure that the correct voltage is supplied by the charger. When adjusting the float and equalized voltage potentiometers, the best procedure first is to lower the voltage until current flowing, as indicated by the ammeter, decreases appreciably. Then, the voltage is adjusted to the proper float or equalized set-point. This procedure helps to eliminate any problems with a needle that is stuck on the panel voltmeter. To achieve correct results, it is important to calibrate the panel voltmeter before adjusting any of the potentiometers.

Float Voltage Adjustment

The setting of the float potentiometer **"FL"** on the instrument panel determines the float voltage level, provided the rocker switch on the instrument panel is in the "Float" position. Turning the potentiometer clockwise increases the float voltage. Turning it counter-clockwise decreases the voltage. In order to adjust the float voltage correctly, the battery should be in a fully charged condition with some load connected. Adjust the float potentiometer only while the equipment is operating.

EQUALIZE VOLTAGE ADJUSTMENT

The potentiometer for this adjustment is also on the instrument panel and is labeled **"EQ."** Move the rocker switch to the **"Equalize" (EQ**) position. Then, with the equipment in operation, make the equalize voltage adjustment. The equalize voltage potentiometer works exactly as the float voltage potentiometer - clockwise turn increases and counter-clockwise turn decreases the voltage.

BATTERY CHARGER TYPE ARU

we will study this charger in details as an example for battery chargers.
The battery charger rating, as on the name plate, is as follows:
AC Input Rating: 240V/480 AC at 30/15 Amps

DC Output Rating: 132 at 50 Amps

MAIN COMPONENTS

The main components of a three-phase ARU series charger are shown in the block diagram of Fig. 3.6-6. AC input power is applied through the input Circuit Breaker to the power transformer. The Circuit Breaker, besides being the AC disconnecting means, provides overcurrent and fault protection in case of a malfunction or a short circuit in the input circuit of the equipment or in the power transformer. Fuses are

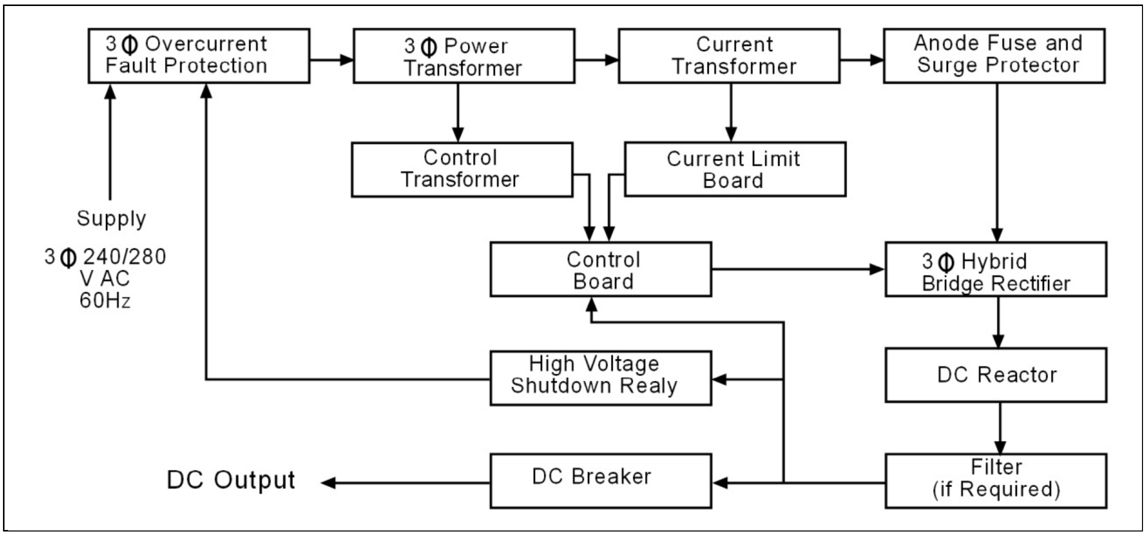


Fig. 3.6-6 Block Diagram of Battery Charger type ARU 130 K50

provided for overcurrent protection when charger is connected to 480 AC input.
The power transformer isolates the DC circuit from the AC supply and changes the level of the AC input voltage to the level required by the DC power circuit. The rectifier unit, which is a three-phase hybrid bridge consisting of 3 thyristors (SCRs)

and 3 diodes, converts the AC power to DC. The thyristors with the control unit also function as the control elements in maintaining constant output voltage within the present current under normal operating conditions.
The thyristors are phase controlled by the control unit to generate the pulses to turn on the thyristors at the proper instant to maintain the charger output voltage/current at the set levels. A signal proportional to the output voltage is fed to the control unit where it is compared against a reference. The differential or error signal thus generated is fed to the phase control and pulse forming circuits in the control unit producing the pulses to fire the thyristors.

Current limit is achieved in a similar manner. A signal developed in the current transformers and the current limit proportional to the output current is fed to the control unit. When it tends to exceed a reference signal, it overrides the voltage control signal to the phase control and pulse forming circuits and thus determines the instant for firing pulses. Anode fuses and surge protectors protect the rectifier unit against faults and transient over-voltages. DC power from the rectifier unit is fed through a smoothing reactor, filter capacitors (optional), and the DC breaker to the battery and the load. The current limit is factory set at 110% of the rated output current of the charger. If a lower current limit setting is desired, it may be set within the range of 90% and 110% of rated DC current.

AC Power Failure Alarm Relay (ACPFAR)

An AC power failure alarm is a three pole double throw 120 VAC relay connected across the primary of the power transformer. When AC power is removed, the relay de-energizes and may be used to provide an alarm signal.

BATTERY CHARGER ROUTINE MAINTENANCE

Before inspections or repairs are performed on battery chargers, both the AC and DC power should be disconnected. Only qualified personnel familiar with the service

procedures in the maintenance manual should work on the equipment since the charger contains high voltages.

INSPECTION

An inspection of the charger should include the following:

1. Check the area around the unit ensuring nothing interfering with the free flow of air through the unit.
2. Blow out the interior of the unit with low pressure dry air to remove dust and dirt accumulations.
3. Check that all connections are clean and tight. Discoloration of any wire or terminal is an indication of loose, corroded, or overheated connections.
4. Check all wiring or conductors for cracked or worn insulation.
5. Check all capacitors for oil leakage, case or seal rupture, etc. Capacitors showing signs of degradation due to excessive leakage should be removed and replaced.
6. Check, adjust float and equalize voltages as per the manufacturer's instructions.
7. If possible, check the operation of current limit, as excessive overload may be damaging.
8. Periodically check indicating meters against portable standards. Using care in doing so, adjust meters with the zero adjusting screw on the face of the meter.

POWER SUPPLY CIRCUITS

Power supply circuits can be very simple or very complex used in some electronic equipment such as fire fighting, alarms, anunciators, communications, automation, protection, and control systems. Some applications required three terminals outputs including positive, negative, and zero terminals. While the other applications need positive and zero voltage only, as shown in Fig. 3.6-7. The power loss across the series regulator is always the difference between the input and output power for,

approximately, the same load current flowing through the input and output terminals, assuming negligible bias current for the regulator feedback circuit (not shown). As a result of the series-pass element in active mode of operation to regulate the output voltage, the efficiency is only in the range of 30-50%.

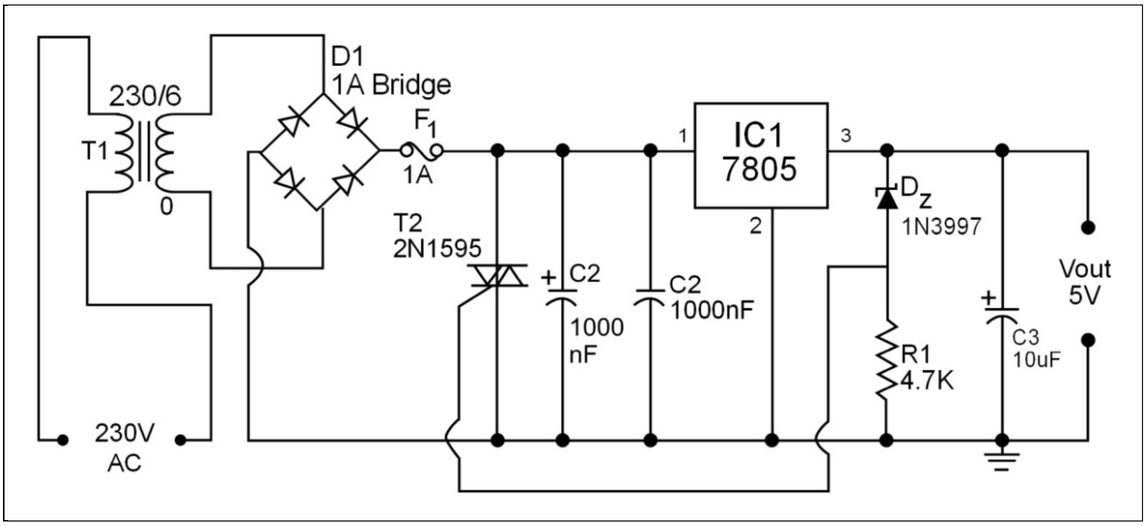


Fig. 3.6-7 Simple Series Pass Power Supply Circuit

SWITCHED MODE POWER SUPPLY (SMPS)

Fig 3.6-8 shows a simple schematic diagram for Switch Mode Power Supply (SMPS). Switched Mode Power Supply utilizes a power semiconductor device either in saturation or cut off mode at high frequency for a controlled period depending on the output voltage and/or current and hence the name, “Switch-mode or Switched Mode”. It aims to save power dissipation at much higher efficiency (75-95%). At no load, the delivered power from the AC or DC supply is at its minimum value. As the load increases, the switching power device remains saturated for longer period to deliver more power at minimum power dissipation. SMPS can deliver power to many different loads at the same time. It also provides regulation, smoothing, filtering, and protection against overload.

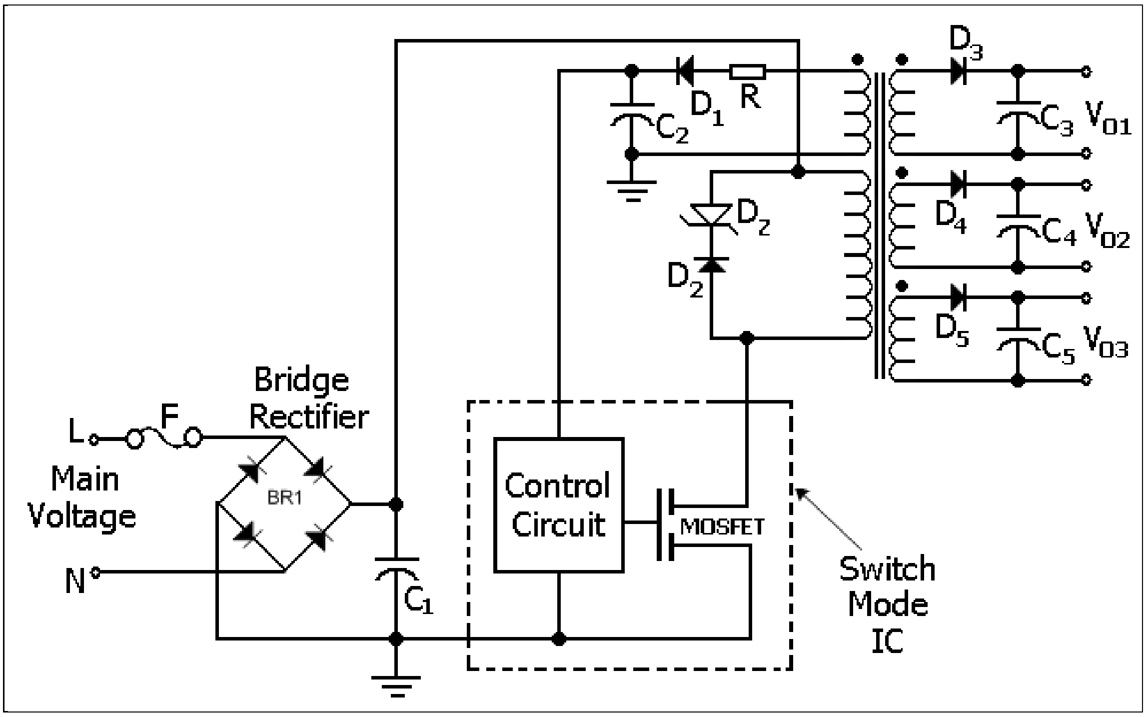


Fig. 3.6-8 Simple Schematic Diagram for Switch Mode Power Supply

POWER SUPPLY FOR RELAYS

Fig 3.6-9 shows a typical schematic diagram for DC/DC converter to supply low voltage DC to relays. Most protective relays electromechanical type, static type, or digital relays need DC supply to operate. Station batteries are the main sources of DC supply for the protective relays. They can deliver 220V or 110V DC, but the protective relays need also DC voltages such as 6V, 12V, 18V, 24V, and 48VDC.

DC-to-DC converter is an electronic circuit with 220VDC input from station DC bus to supply all the required DC voltages.

DC to DC converter either feeds electromechanical relays externally or through a Printed Circuit Board (PCB) included in the static or digital relay circuits. DC to DC converter works as a switch mode power supply with all its features.

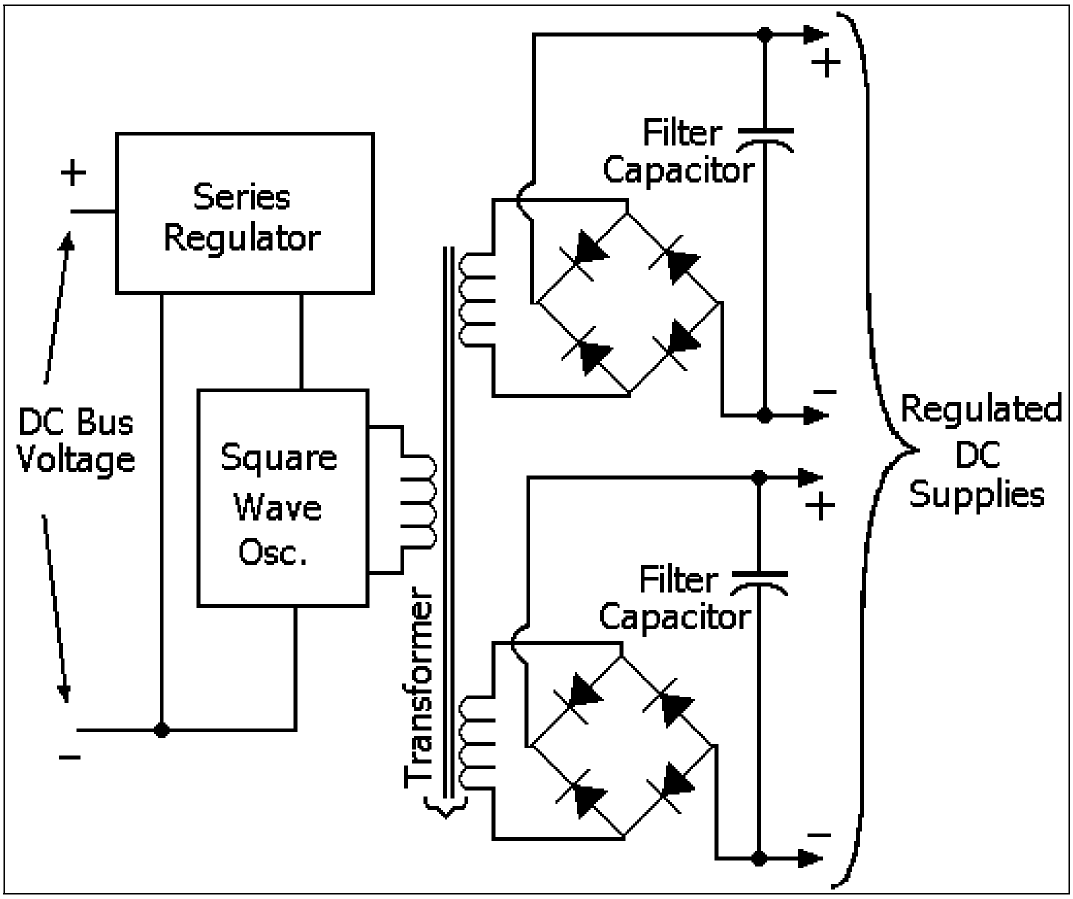


Fig 3.6-9 DC-to-DC Converter Circuit with Two Different Outputs

Fig. 3-6-9 depicts the block diagram of a DC supply for a protective device.

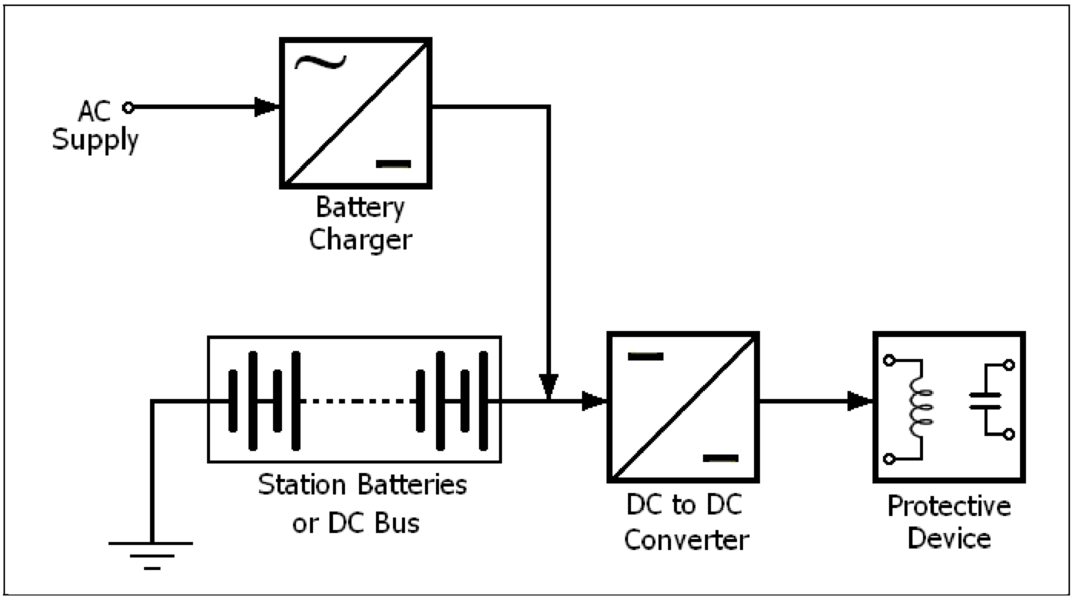


Fig. 3.6-10 DC Supply for Protection System

UNINTERRUPTIBLE POWER SYSTEM (UPS)

Sometimes there is a need to provide high quality AC with transient free "conditioned" power to critical loads (SCADA for example) at all times despite variations in the grid feed and also providing continuous uninterrupted power in the event of failure of grid power. There are many types of UPS used in SEC such as "Gould" solid state UPS and "Cyberex" UPS, as shown in Fig. 3.6-10. The UPS, consisting of built-in inverters, supplies 120 AC voltage at stable 60 Hz frequency These inverters will, not only change AC into DC, but will also change DC into AC voltage. The system is designed to operate automatically, whereby it will change from one inverter to another if a fault occurs. A third inverter is operated manually if the two inverters break down at the same time. The system may include a bank of batteries, which would take over in the event of losing all other supplies.

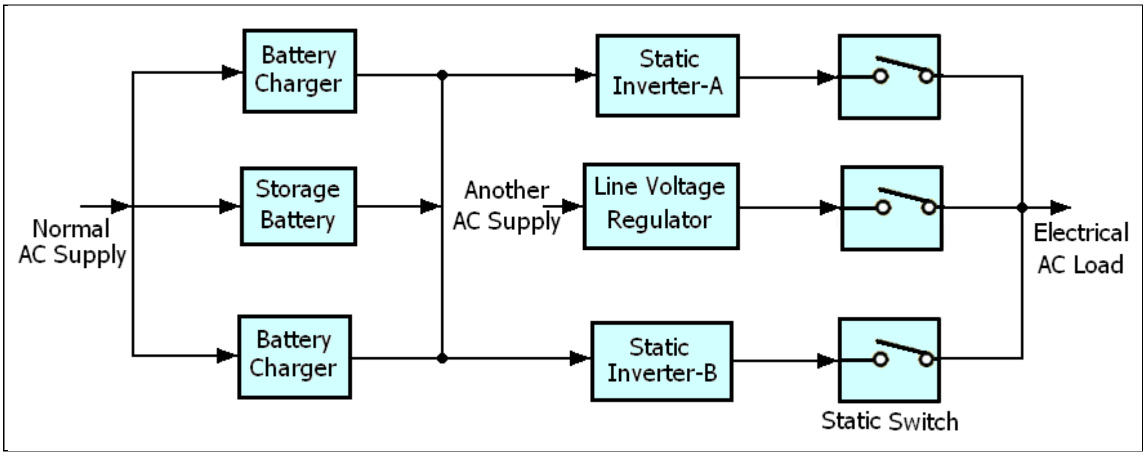


Fig. 3.6-11 UPS Block Diagram

The AC voltage from inverters feeds the load (SCADA equipment for example) for a short period of time (1/2 hour or one hour) until emergency generator starts.

SUMMARY

Three-phase half-wave uncontrolled rectifier uses three diodes.

Three-phase full-wave bridge uncontrolled rectifier uses six diodes.

Three-phase full-wave bridge fully controlled rectifier uses six thyristors.

The controlled devices always need trigger pulses at the right instant in right sequence to operate properly.

- The charger voltmeter is calibrated with a portable voltmeter standard for accuracy of the readings.
- Always adjust the Equalize **(EQ)** or Float **(FL)** voltage in a fully charged battery condition with some load connected.
- The battery charger circuit consists of step down transformer, power rectifiers, smoothing capacitor, voltage regulator, and filter circuit.
- Switched mode power supply uses static oscillator to control the output DC voltage.
- UPS is an emergency power supply that stores energy in chargeable battery to produce it when the main power fails.
- UPS circuit consists of rectifier, inverter circuits, and battery.
- UPS equipment produces temporary AC power instead of the main power for a certain time depending on the total ampere-hour of the battery.

GLOSSARY

Rectifier:	Circuit to change AC voltage to DC
Inverter:	Circuit to change DC voltage to AC
Battery Charger:	Power electronic circuit changes AC to DC
Controlled rectifier:	Devices need to pulse trigger in order to conduct
Uncontrolled:	Don't need pulse to trigger (diode)
Solid state charger:	Charger built from power semiconductors
Switched mode power supply:	Advanced type of power supply, depends on switching static contact oscillator.
Calibration:	Adjusting to zero error
UPS:	Uninterruptible Power Supply
EQ:	Equalize
FL:	Float
SCADA:	Supervisory Control and Data Acquisition

REVIEW EXERCISE

1. Three-phase Half-Wave rectifier uses ______ diodes for FW rectification.
   a) 3 b) 4
   c) 5 d) 6
2. Three-phase Full-Wave rectifier uses ______ diodes for FW rectification.
   a) 3 b) 4
   c) 5 d) 6
3. The function of voltage regulator is:
   a) To control the input voltage. b) Smooth the output waveform.
   c) To keep output DC voltage constant. d) To protect the power supply circuit.
4. Switched mode power supply uses input step down transformer.
   a) True b) False
5. Adjust the Equalize **(EQ)** or Float **(FL)** potentiometer only when battery is fully charged and connected to the equipment in operation.
   a) True b) False
6. List the four major components of the Protection System Supply in Fig. 3.6-12.
   1- -- 2- --
   3- -- 4- --

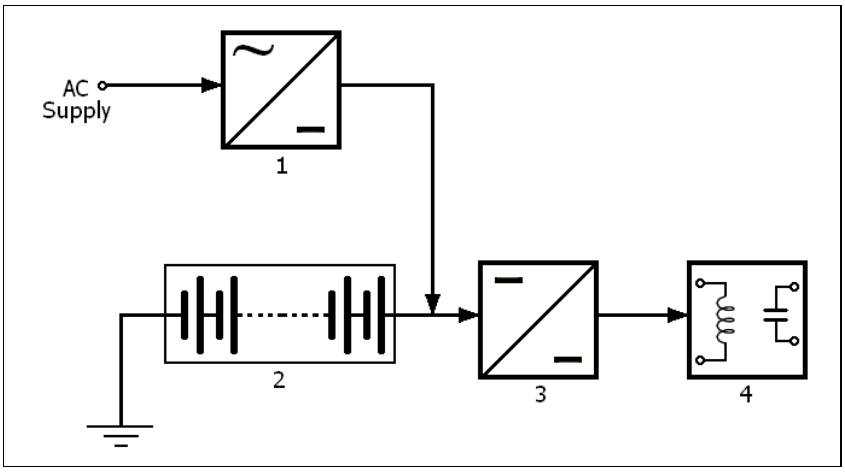


Fig. 3.6-12 Protection System DC Supply

TASK 3.6-1
INSPECTION AND CALIBRATION
FOR BATTERY CHARGER

OBJECTIVES

Upon completion of this task, the participants will be able to:

- Inspect and calibrate the battery charger.

TOOLS, EQUIPMENT & MATERIALS

1- Battery charger.

PROCEDURE

1. Receive from the instructor, the following:

    - Battery charger
    - Operating instructions for charger
    - Safety equipment

2. Inspect the charger for any sign of excessive heat by feeling the outside of the charger to determine if the charger is too hot.

3. Clean the dust from interior of the charger, using vacuum cleaner.

TO ENERGIZE CHARGER

4. Place the "Normal Equalize" toggle switch in "Normal Position".
5. Close the DC circuit breaker. The DC voltmeter on the front panel should read the battery voltage. If the charger has the filter capacitors across the DC output, the battery will charge them when power is switched on initially causing a surge current.

6. Close the AC circuit breaker, the output current will build up gradually.

Note *Energizing the charger without the battery or load connected to it, will cause high voltage shutdown tripping the AC breaker.*

FLOAT VOLTAGE ADJUSTMENT

7. The setting of the float potentiometer "FL" on the instrument panel determines the float voltage level of the charger (provided the toggle switch, also in the instrument panel is in the "Normal" (float position). Turning it counterclockwise decreases the output voltage.

8. To adjust the float voltage correctly, the battery should be in a fully charged condition with some load connected. Adjust the float potentiometer only while the charger is operating.

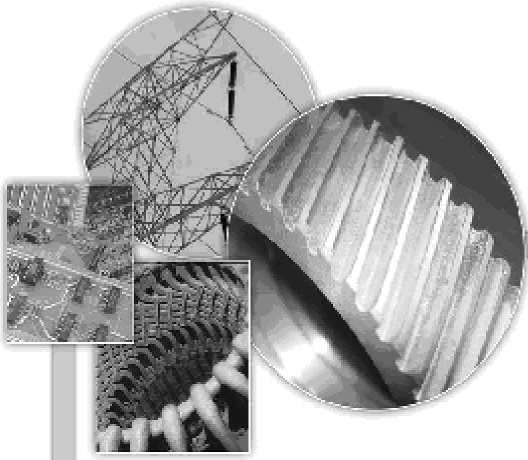
NOTE Keep the toggle switch in the "Float" (normal) position during regular operation.

Equalize voltage adjustment The equalize voltage potentiometer is located on the charger instrument panel and is identified as "EQ".

9. Move the toggle switch to the "Equalize" position. Then, with the charger in operation as it was during float voltage adjustment, make the equalize voltage adjustment.

The equalize voltage potentiometer works the same as the float voltage potentiometer - a clockwise turn increases voltage; a counter-clockwise turn decreases voltage.

Note *If used with lead calcium batteries, (not requiring equalizing), the equalized potentiometer should be adjusted to zero (full OCW) to minimize the possibility of overvoltage on the load.*



UNIT 4

FAULT CONDITIONS & CALCULATIONS

UNIT-4
FAULT CONDITIONS & CALCULATIONS

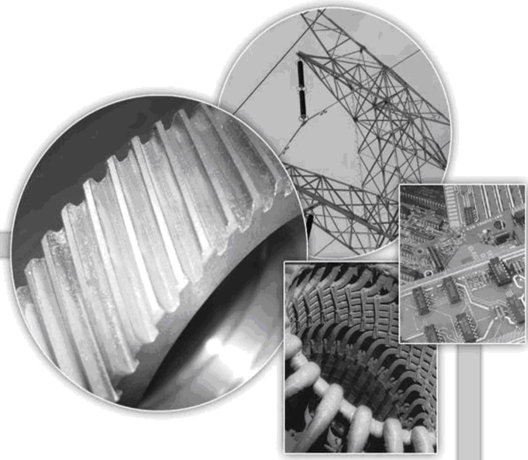
OVERVIEW

In this unit, the trainees learn the importance of complex numbers in single and three phase RLC circuits, representing vector diagrams of the power circuit components, and the action of symmetrical components to describe and solve abnormal conditions.

OBJECTIVES

Upon completion of this unit, the trainees will be able to:

- Identify the fault nature, their causes, and related calculations.
- Verify the complex numbers and their applications.
- Demonstrate the vector diagram representation.
- Illustrate the symmetrical components and their applications.



LESSON 4.1

FAULT CONDITIONS & PROTECTION REQUIREMENTS

LESSON 4.1
FAULT CONDITIONS & PROTECTION REQUIREMENTS

OVERVIEW

This lesson discusses fault conditions in transmission and distribution system and their causes. It also discusses the different types of electrical faults.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- List types of electrical faults and their causes.
- Gain awareness for the types of TL faults.
- Illustrate the difference between phase faults and earth fault.
- Demonstrate the behavior of current and voltage during faults.
- Identify the requirements for protection system.

INTRODUCTION

Fault current means the current that starts from the voltage source, passing through electrical circuit part, shorting to ground or to other phase(s) and not the load. Fault current may continue through earth or between the circuit lines.

TYPES OF ABNORMAL CURRENT

LEAKAGE CURRENT

It is the current, which starts from the voltage source and continues through weak or defective insulation.

TRANSIENT CURRENT

It is the starting current in the rotating machines, (or short circuit) higher than normal for few seconds (or few cycles in case of short circuit) until it settles to a steady state condition.

OVERLOAD CURRENT

It is the excessive current greater than normal, which starts from the voltage source and continues through the low impedance load causing abnormal temperature rise in the circuit components.

PHASE FAULT

It is the current from voltage source passing between phases of one or more transmission lines, and is limited only by the total circuit impedance excluding load.

EARTH FAULT

It is the current from voltage source through the line to earth and is limited by the total circuit impedance plus earth resistance.

CUMULATIVE FAULT CURRENT

It starts with any abnormal fault current continuing with another type of fault current until the protection device trips and the fault is cleared.

TYPES OF FAULT NATURE

Faults are classified as non-persistent and persistent fault types.

NON-PERSISTENT FAULT

It is a momentary fault removed by interruption of the current in the faulty circuit. Protection system responses to trip under any type of fault including transient fault until the system closes again. Non-persistent faults represent more than 65% of the total faults, and may be caused by lightning, conductors swinging together momentarily, tree limbs making momentary contact with conductors, etc. If a fault that is initially transient in nature and is not cleared immediately, either through self-clearing or a protective device, the characteristic and nature of the fault may change and the fault may become permanent.

PERSISTENT FAULT

Permanent fault is a continuous re-occurring fault. It may continue regardless of the protection speed of the protective device used or the number of times the device opens and recloses the circuit. The permanent faults represent 35% of the total faults, and

may be caused by conductors broken by trees or burnt down by arcs, foreign objects across conductors, lines down due to broken poles and equipment failure.
Operating experience shows that the majority of faults that occur on overhead circuits are initially non-persistent in nature. Operating records show that these faults may be as high as 70 to 80 percent of the total number of faults on some systems. Because of the high percentage of non-persistent faults that occur on overhead systems, they should be taken into consideration while establishing over current protection practice.
If a fault is not cleared within a given period of time, depending upon the type of fault, the chances are that the fault becomes persistent in nature and cannot be cleared by interrupting. The speed of operation of an over current protective device influences the nature of the fault in many cases. For example, if two conductors with faulty weatherproof covering should swing together in such a way as to establish an arc between them, it is very possible that the conductors may burn down at the arc point if the circuit clearing time is too long. This is a case in which a fault that is initially non-persistent in nature becomes persistent.

TYPES OF FAULTS

Power systems may be subjected to four types faults:

- Three-phase with and without earthing connection
- Phase-to-phase (two-phase)
- Phase-to-earth (single-phase)
- Double phase-to-earth (phase-phase-earth)

Faults sometimes occur simultaneously at separate points on the system and on different phases, such as cross-country faults. Sometimes they are accompanied by a broken conductor or may even take the form of a broken conductor without earth connection. All of these are applicable to lines and feeders, but the principal ones are common. In addition to the above faults, generators, transformers and motors are also subjected to short circuits between turns of the same winding.

With the exception of the three-phase short circuit with or without earth connection, all of the faults listed represent unbalanced conditions in a three-phase system with which we are mainly concerned. The accurate electrical analysis of possible fault conditions is vital to the correct design and application of protection.

TRANSMISSION LINE FAULTS

Compared with bus bars, generators, and other power equipment, transmission lines are very long extending out of the power stations to the valleys and deserts. Furthermore they are exposed to natural hazards such as lightning.

NATURE AND CAUSES OF FAULTS

PRIMARY SYSTEM FAULTS

The major natural causes of faults on overhead circuits, are wind, falling trees, lightning and equipment or wiring failures. Other common causes of faults are human error, glaze, snow and foreign objects. On the other side in underground circuits where the conductors and apparatus are not exposed to the elements listed above, the major causes of faults are equipment or wiring failures and human error. The nature of a fault is simply defined as any abnormal condition, which may cause failure in the insulation strength between phase conductors or between phase conductors and earth or any earthed screens surrounding the conductors. In practice, low impedance is not regarded as a fault until it is detectable. A fault current is caused by a reduction of the impedance between conductors or between conductors and earth to a value below that of the lowest load impedance normal to the circuit. Thus, although pollution reduces the insulation strength of the affected phase, a high degree of pollution on an insulator string does not become a fault until it causes a flashover across the string. This in turn produces excess current or other detectable abnormality.

Pollution is commonly caused by deposited soot or cement dust in industrial areas, and by salt deposited by wind-borne sea spray in coastal areas. Other causes of faults on overhead lines are birds, aircraft, lightning, fog, ice and punctured or broken

insulators, open circuit conductors, abnormal loading in machines, cables and transformers insulation failure because of moisture, mechanical damage, accidental contact with earth or earthed screens, flashover in air caused by over voltage, abnormal loading etc.

NON-SYSTEM FAULTS

Another type of fault is the **non-system fault** related to protection, which results in the tripping of Circuit Breakers without an accompanying fault on the primary system. Such non-system faults may be the result of defects in the protection (incorrect settings, faulty or incorrect connection) or human error in testing or maintenance work. A non-system fault is principally defined as any incorrect Circuit Breaker operation resulting from a cause other than a system fault condition. This definition excludes, however, incorrect Circuit Breaker operations due to incorrect manual operation. However, the manual operation of a Circuit Breaker on receipt of a voltage transformer Buchholz alarm in order to disconnect the voltage transformer from the system is classed as a fault since such disconnection is obligatory. The fault is classified as a system fault if the alarm is genuine and as a non-system fault if it is not.

TYPES OF OVERHEAD LINE FAULTS

Overhead transmission line faults can be classified as follows:

a) Short Circuit b) Open Circuit c) Ground

Any line fault may be due to only one of the above or a combination of any or all of them. Fig. 4.1-1 shows various types of transmission line faults such as insulator arc over short circuit, conductor failure and conductor ground.

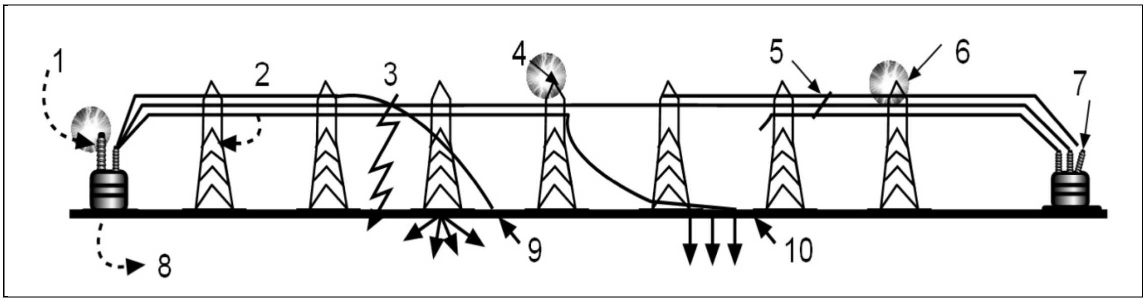


Fig. 4.1-1 Transmission Line Faults

1	Arc-over across entrance bushing	2	Arc-over between conductor and pole
3	Lightning	4	Arcing ground between line and pole
5	Foreign objects falling across line	6	Periodic leakage across insulator
7	Unsymmetrical circuit interruption	8	Arc-over between primary and case
9	Conductor failure	10	Conductor ground

SHORT CIRCUIT FAULT

The following figure shows the different types of short circuit faults.

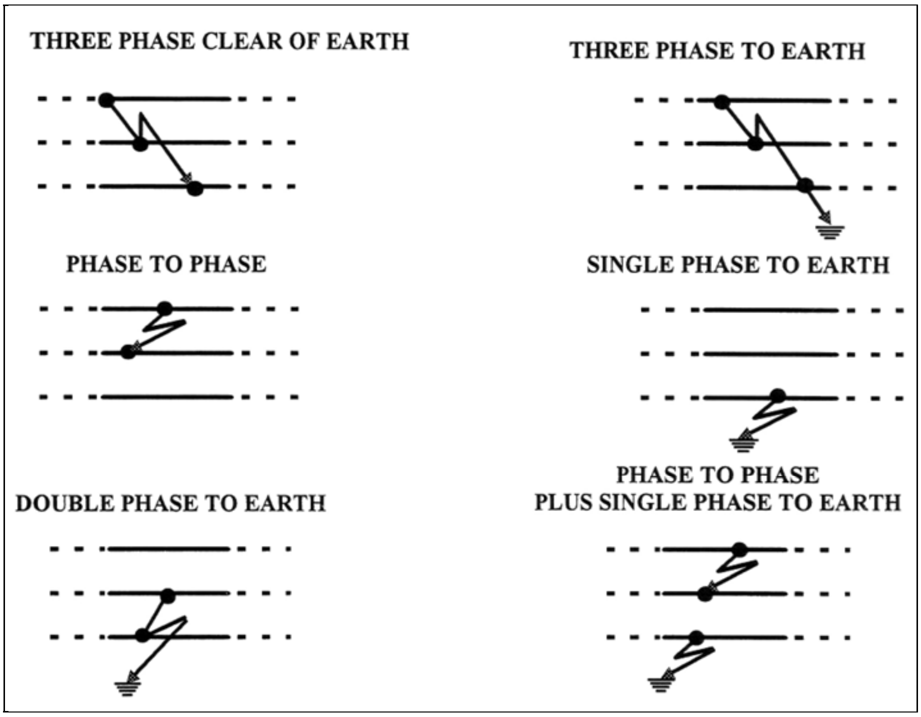


Fig. 4.1-2 Short Circuit Faults

A line is said to be **short-circuited** when two or more of the conductors of the line come in contact with each other. A simple **cross** or short circuit is shown in Fig. 4.1-3. It is evident that when two or more of the line conductors become crossed the resulting short circuit will cause heavy currents to flow in the line. These currents will be so large that they will cause the relays to trip, thereby disconnecting the defective line.

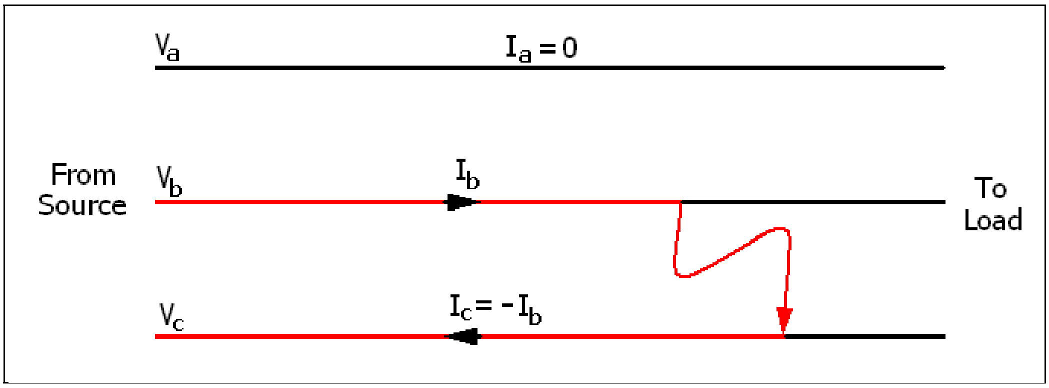


Fig. 4.1-3 Cross or Short Circuit across two Line Conductors of 3-ϕ Line

OPEN CIRCUIT

A line is said to be **open-circuited** when one or more of the conductors of the line are broken and the broken ends are separated, as shown in Fig. 4.1-4. Broken conductors may be caused by heavy rain and wind, causing an excessive weight on the conductors or they may be burnt apart in case of an accidental short circuit and resulting arcing. A broken conductor besides causing an open circuit often causes a ground fault at the loose end. The breaking of the conductor permits the ends to fall to the ground and come in contact with the earth. The cross or short circuit may, therefore, cause the other two faults (open circuit and ground faults) at the same point on the line. Although the first fault was only a cross, the result may be a short circuit, open circuit and ground.

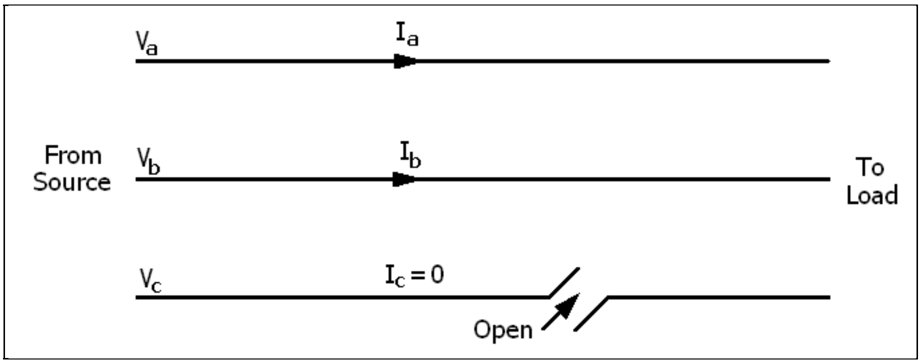


Fig. 4.1-4 Open in One Conductor of 3-ϕ Lines

Fig. 4.1-5 Connection Jumper may be exposed to Open Circuit without ground fault

GROUND FAULTS

Single-phase to ground fault is the most common type of fault that occurs on TL. A line is said to have a **ground** fault when one or more of the line conductors are in contact with the earth. A line may become grounded and yet continue to operate. This is possible if the line system is ungrounded, the line with an accidental ground is shown in Fig. 4.1-6.

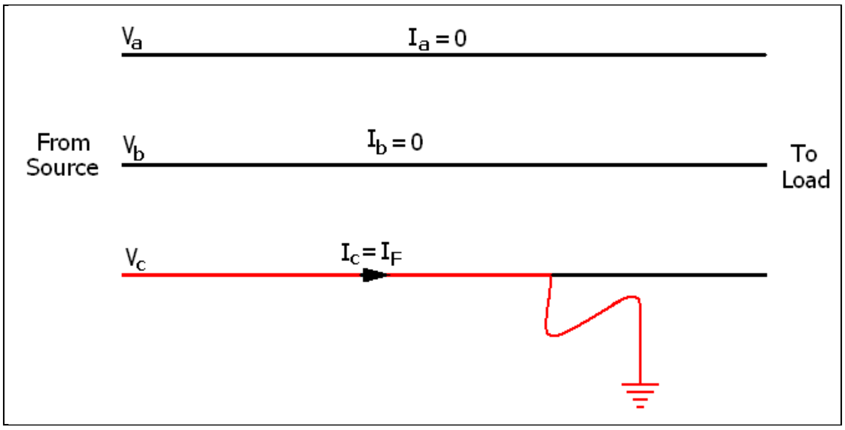


Fig. 4.1-6 Accidental Ground on One Conductor in a Grounded System

This ground, of course, is not desirable, but it will not interrupt the service, as it is not causing a short circuit. Fig. 4.1-7 shows a line with a permanent ground and an accidental ground on one of the line conductors. It will be noted that this is the same as a short across the two grounded conductors. Therefore, a heavy current will flow, which will open the breakers and disconnect the defective lines.

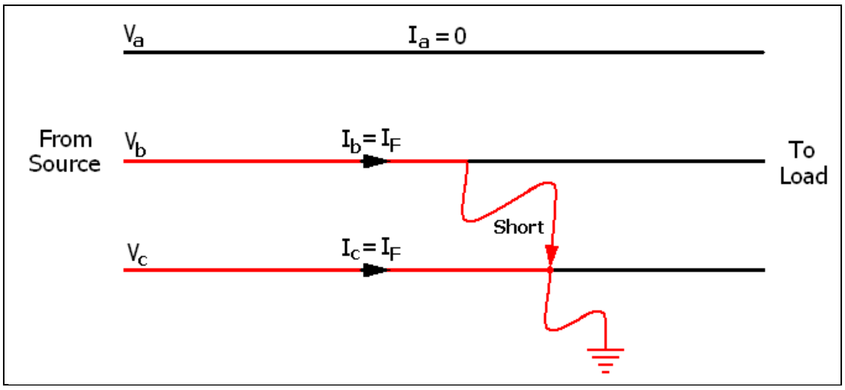


Fig. 4.1-7 Permanent Ground and Accidental Ground causing Short Circuit

INTERTURN FAULTS IN GENERATOR AND TRANSFORMER WINDINGS

Short circuit occurring in the transformer or generator windings are called inter-turn fault. Fig. 4.1-8 shows the different types of these faults.

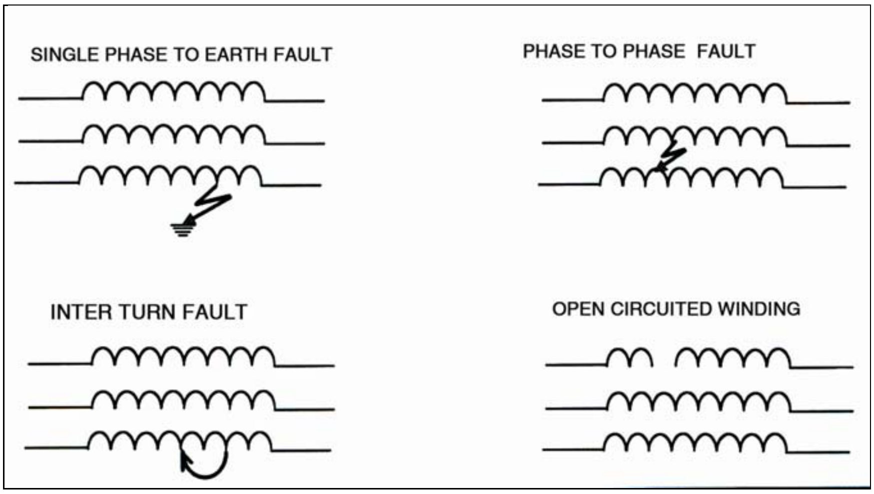


Fig. 4.1-8 Inter-turn Fault and Open Circuit

PRIORITY EQUIPMENT FOR PROTECTION

Transformers and generators are the most important equipment that are susceptible to insulation failure of transformer winding, tap changer failure, etc. Usually most of the substations are equipped with two or more transformers operating in parallel and it is essential that a fault in one will be isolated without affecting the other.

PROTECTIVE RELAYS

Protective relays are a form of active insurance. By their application in all of the power system, fault is quickly detected and action initiated to isolate the damaged parts.

A relay makes a measurement or receives a control signal and consequently makes sudden pre-determined changes in one or more electrical circuits. A protective relay responds to abnormal conditions in an electrical power system to control a Circuit Breaker to isolate the faulty section of the system with the minimum interruption to service. Relays may be categorized into two classes by definition, measuring and controlling functions. Measuring relays in general receive and measure fundamental system quantities. All measurements involve comparison, either of one input quantity or more than one input quantities.

PROTECTION REQUIREMENTS

An effective protective system has the following requirements:

Reliability: A system adequately and dependably ready for all types of faults.

Selectivity: Maximum continuity of service through isolation of only the faulty section of the system.

For example, as shown in Fig. 4.1-9, if we consider the system shown, in case of fault at point F_1, Circuit Breaker CB_1 only will trip and in case of fault at F_2, CB_2 and CB_3 only will trip. In case of fault at points F_3 or F_4, CB_4 and CB_5 only will trip.

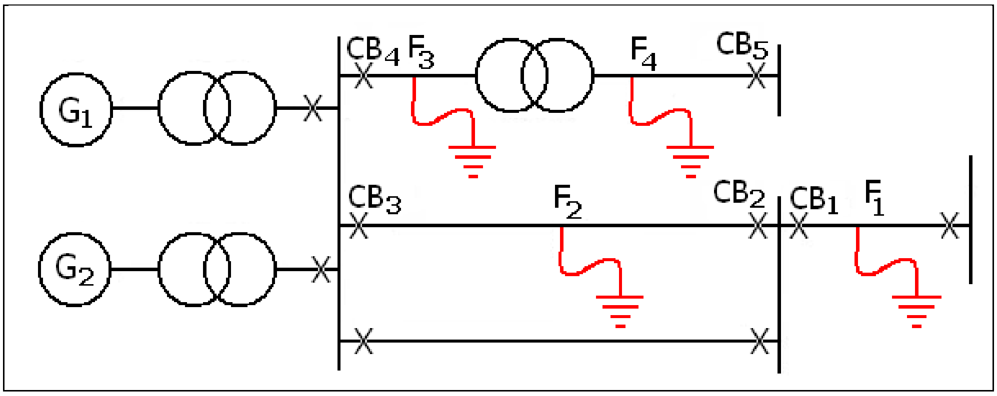


Fig. 4.1-10 Protective Relay Selectivity

Speed: Faults must be cleared as quickly as possible to avoid damage to equipment. The time required to identify and isolate the faulty circuit is the clearing time:

- Fault clearing time = Relay time + Circuit breaking time
- The relay time is the time between fault occurring and relay contacts closing.
- The time of circuit breaking is the time it takes for Circuit Breaker mechanism to interrupt the circuit.

Simplicity: Minimum components and circuits.

Economy: Minimum cost with maximum quality.

Any relaying equipment must be sufficiently sensitive so that it operates reliably and promptly, when required as the fault condition detected. It must be able to select

between those conditions for which prompt operation is required and those for which no operation or time delay operation is required. In addition, it must operate at the required speed. The ultimate goal of protective relaying is to disconnect a faulty system element as quickly as possible. Sensitivity and selectivity are essential to ensure that the proper Circuit Breakers trip and speed is critical to minimize damage.

FACTORS INFLUENCING PROTECTION SELECTION

Some of the factors, which influence the protection applied, are:
Economics: Initial, operating and maintenance costs.

Operating Practices: agree with the existing standards and practices, permitting efficient system operation and flexible for foreseeable future changes.

Previous Experiences: Protection frequently emphasized for troubles previously experienced and de-emphasized for troubles not encountered.
Available Indications of Faults: Fault magnitudes, location and connection of instrument transformer and devices.

RELAY CLASSIFICATIONS

Relays are classified to four classes as follows:

Protective Relays

It detects defective equipment or dangerous and undesired conditions, then initiate or permit suitable switching or to give adequate warning or operate an auxiliary relay.
For example overcurrent, undervoltage, frequency and distance relays.
Auxiliary Relays
It operates to control another relay or device for higher power control function. The auxiliary relay is controlled by a protective relay. Another function is to give multiples contacts with different types.

Regulating Relays

It operates when an operating quantity increases or decreases above or below a predetermined limit, respectively, by directing a signal to an auxiliary equipment to restore the quantity to the predetermine limit. For example automatic voltage regulator (AVR).

Monitoring or Verification Relays

Its function is to verify power system conditions with respect to prescribed limits and to initiate or permit automatic functions other than opening a Circuit Breaker during fault conditions. For example pressure relay, which monitors the SF6 pressure and verify that the pressure is within the limit otherwise it blocks circuit breaker.

Programming Relays

It follows operating sequences. It may be used for reclosing and synchronizing.

PRINCIPLES OF OPERATION

Relays must continuously monitor power circuit parameters such as current and voltage magnitudes, phase angle relationships, direction of power flow and frequency. When an intolerable circuit condition, such as a short circuit is detected, the relay responds and closes its contacts and the abnormal portion of the circuit is de-energized via the Circuit Breaker(s). In addition, the relay can also provide alarm signals and lockout functions. Since no single relay can be designed to monitor and respond to every abnormal condition that can occur in an electrical system, it is necessary to gain a basic understanding of operation, design and construction variations.

All protective relays, regardless of complexity, use either one or more of the following basic operating principles:

- Electromagnetic relays
- Static relays

- Numeric (digital) relays

SUMMARY

- A non-persistent fault is a momentary fault removed (cleared) by fast tripping (interruption) for the circuit.

- A permanent fault is a fault remains regardless of the speed of the protective devices.
- The principle types of power system faults are:
  - Three-phase with and without earthing connection
  - Phase-to-phase
  - Phase-to-earth (single-phase)
  - Double phase-to-earth (phase-phase-earth)
- The major causes of faults on overhead circuits are wind, trees, lightning, faulty equipment, wiring failures, human error, glaze, snow, foreign objects, pollution (soot, dust), birds, aircraft, weather (fog, ice), punctured or broken insulators, open circuit conductors, abnormal loading of machines, cables and transformers (moisture, mechanical damage, overheating).
- A line is said to be **short circuited** when two or more of its conductors come in contact with each other.
- A line is said to have a **ground** fault when one or more of the line conductors are in contact with the earth.
- Relays may be categorized into two classes, those that measure (e.g. protective relays) and those, which merely repeat a controlling function (auxiliary relays).
- The ultimate goal of protective relaying is to disconnect a faulty system element as quickly as possible for which Sensitivity and Selectivity are essential to ensure that the proper Circuit Breakers will be tripped and speed is critical to minimize damage.

GLOSSARY

Transient Fault:	Momentary
Permanent Fault:	Continuous breakdown
Economy:	Minimum cost with highest quality
Simultaneously:	At the same time
Ground fault:	Fault between conductor and ground
Phase fault:	Fault between phase conductors
Simplicity:	No complication
Reliability:	Dependability without interruption

REVIEW EXERCISE

1. The most important equipment to be protected is _____________ and ______________.

2. Faults are classified as _____________ or ________________ in nature.

3. The ___________ faults are caused by lightning, conductors swinging together momentarily or tree limbs making momentary contact with conductors.

4. If a transient fault is not cleared rapidly, either through self-clearing or the operation of a protective device, the characteristic and nature of the fault may change and the fault may become __________ in nature.

5. The ________ faults are caused by conductors broken by trees or burnt down by arcs, foreign objects across conductors, lines down due to broken poles and equipment failure.

6. List the three types of overhead transmission line faults:
   a)
   b)
   c)

7. A line is said to be **open-circuit** when one or more of the conductors of the line are broken and the broken ends are separated
   a) True b) False

8. Persistent faults occur much more than non-persistent faults.
   c) True d) False

9. Double lines to ground fault occurs in the transformers and generators.

   e) True

   f) False

10. List the four types of power system faults:

    a)

    b)

    c)

    d)

11. A fault current is caused by a reduction of the ___________ between conductors or between conductors and earth to a value below that of the lowest load ___________ normal to the circuit.

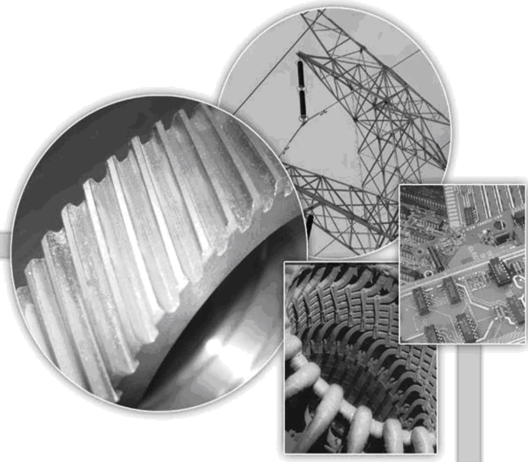
12. Leakage current occurs because of

    a) Sudden high voltage

    b) Overload

    c) Insulation weakness

    d) Broken conductors



LESSON 4.2

COMPLEX NUMBERS

LESSON 4.2
COMPLEX NUMBERS

OVERVIEW

This lesson discusses the use of Complex Numbers in RLC combination AC circuits. It facilitates the calculation of magnitudes and phase angles for electrical quantities of AC circuits.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Perform calculations for scalar and vectorial quantities.
- Perform mathematical addition, subtraction, multiplication, and division for the complex numbers.
- Represent electrical circuit components with complex quantities.

INTRODUCTION

Complex numbers form numerical systems that include the phase angle of an AC quantity with its magnitude. Therefore, the complex numbers are useful in AC circuits when the reactance of X_L or X_C makes it necessary to consider phase. Any type of AC circuit can be analyzed with complex numbers.

COMPLEX NUMBERS

A. OPERATOR (j):

The Operator (**j**) is the unit that indicates 90°, (Fig. 4.2-1). The **j** is usually written before the number representing an Imaginary quantity.

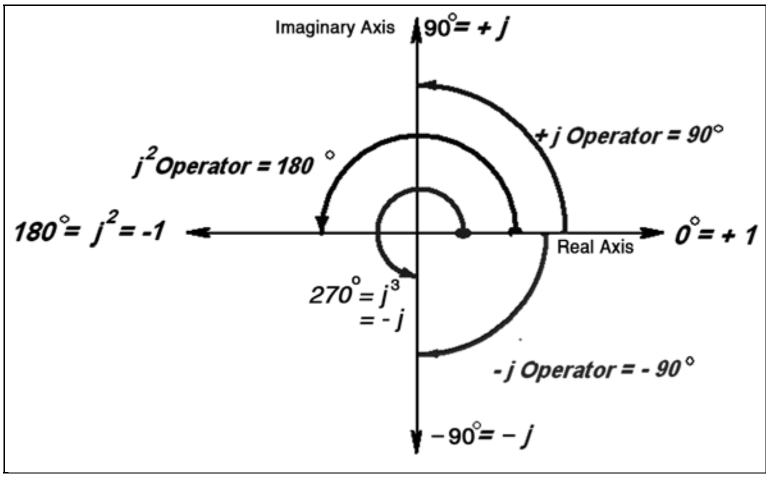


Fig. 4.2-1 Operator (**j**)

In mathematics, numbers on the horizontal X-axis are Real numbers, including positive and negative values. Numbers on the **Y-**axis (j-axis) are called Imaginary numbers, only because they are not on the real axis. In electricity, however, j is used to avoid confusion with I as the symbol for current. Furthermore, there is nothing imaginary about electrical quantities on the **j-**axis. An electrical shock from **j** 500 V is just as dangerous as 500 V positive or negative.

The characteristics of **j** operator are:

0° = 1 as a factor

90° = j as a factor

180° = j^2 as a factor = -1 as a factor

270° = j^3 as a factor = (j^2 x j) = -j as a factor

360° = = j^4 as a factor = (j^2 x j^2) = 1 as a factor

DEFINITION OF COMPLEX NUMBER

The combination of a real and imaginary term is a complex number. Usually, the real number is written first. As an example, **(3 + j 4)** is a complex number including 3 units on the real axis (X-axis) added to 4 units 90° out of phase on the **j**-axis. The name complex number just means that its terms must be added as phasors.

The phasors for several complex numbers are shown in Fig. 4.2-2. Note that +**j** phasor is up for 90°, the **-j** phasor is down for -90°.

The phasors are shown with the end of one joined to the start of the next to be ready for addition. Graphically, the resultant sum is the hypotenuse of the right triangle that its sides are the two phasors. Since a number like (3 + j 4) specifies the phasors in rectangular coordinates, this system is the rectangular form of complex numbers.

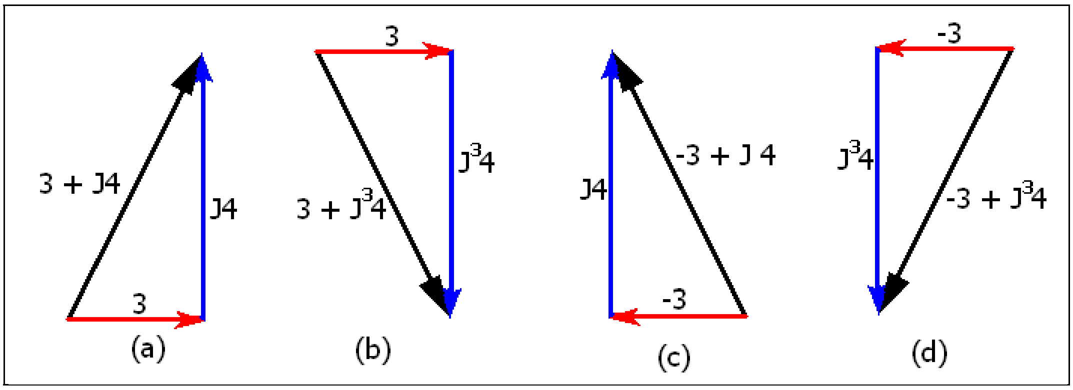


Fig. 4.2-2 resultant Phasor corresponding to Real (R) and j (Im) Terms in Rectangular Coordinates (R ± j Im)

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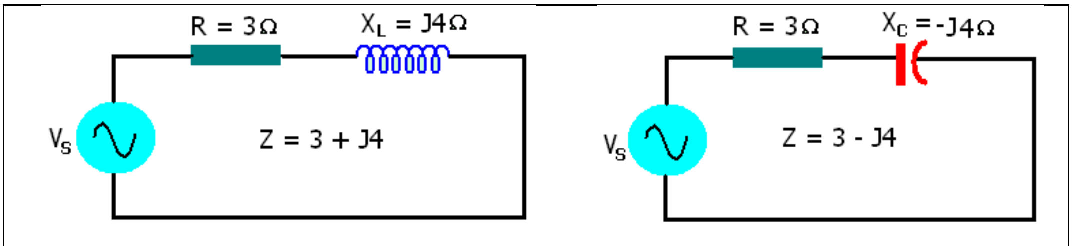


Fig. 4.2-3a RL Circuit

Fig. 4.2-3b RC Circuit

Fig. 4.2-3 Impedance as Complex Quantity

In circuit (a), **0°** or real number without **j** operator is used for resistance (**R**). 9**0°** or + **j** is used for inductive reactance $\mathbf{X_L}$. For example, X_L = 4Ω is **j** 4Ω**.** This always applies to X_L, whether it is in series or parallel with R. **-90°** or **-j** is used for capacitive reactance X_C. This rule always applies to X_C, whether it is in series or parallel with R. The multiple impedance written as complex numbers can be calculated as follows:

$\mathbf{Z_T = Z_1 + Z_2 + Z_3 +}$ for series Impedance

$\mathbf{(1/Z_T) = (1/Z_1) + (1/Z_2) + (1/Z_3) +}$ for parallel Impedance

Fig. 4.2-4 shows examples of series and parallel impedances.

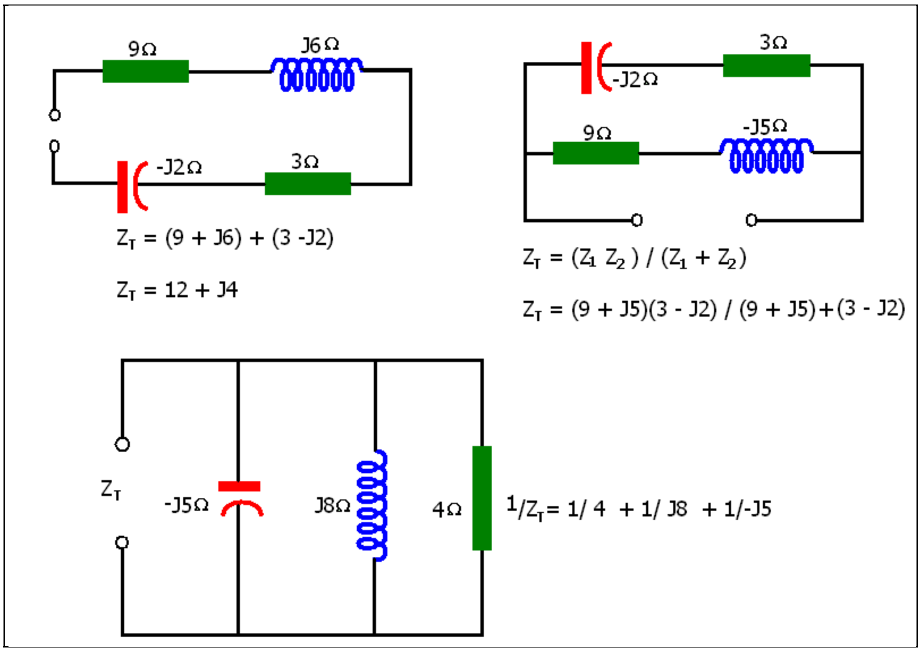


Fig. 4.2-4 Series and Parallel Impedances in Complex Quantities

COMPLEX NUMBER IN POLAR FORM

$$\mathbf{Z} = \sqrt{\mathbf{R}^2 + \mathbf{X}_L^2}$$

$$\theta = \mathbf{tan}^{-1} \frac{\mathbf{X}_L}{\mathbf{R}}$$

$$\mathbf{R} = \mathbf{Z} \cos \theta$$

$$\mathbf{X}_L = \mathbf{Z} \sin \theta$$

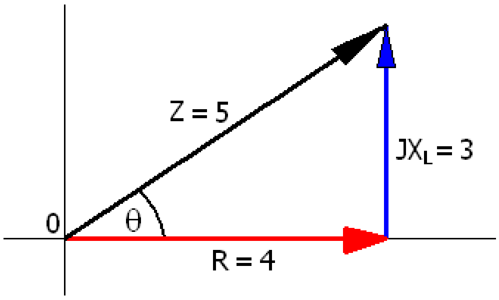


Fig. 4.2-5 Complex Numbers in Polar Form

In electrical terms a complex impedance (**4 + j 3**) means **4** Ω of resistance and **3** Ω inductive reactance with a leading phase angle of 90°, (Fig. 4.2-5). The magnitude of combined **Z** is equal $\sqrt{16+9} = 5\Omega$. The phase angle of the resultant is the angle whose tangent is 3/4. The angle θ equals 37°.

4 + j3 = 5 $\angle 37°$

When calculating the tangent ratio, note the j term is the numerator and the real term is the denominator. With a negative j term, the tangent is negative, which means a negative phase angle. The following examples are applications of complex numbers in polar form:

$2 + j\,4 = \sqrt{4+16}\,\underline{/\tan^{-1}(2)} = 4.47\ \angle 63°$

$4 + j\,2 = \sqrt{16+4}\,\underline{/\tan^{-1}(1/2)} = 4.47\ \angle 26.5°$

$8 + j\,6 = \sqrt{64+36}\,\underline{/\tan^{-1}(3/4)} = 10\ \angle 37°$

$4 - j\,4 = \sqrt{16+16}\,\underline{/\tan^{-1}(-1)} = 5.66\ \angle -45°$

$5 - j\,0 = \sqrt{25+0}\,\underline{/\tan^{-1}(0)} = 5\ \angle 0°$

$0 + j\,5 = \sqrt{0+25}\,\underline{/\tan^{-1}(\propto)} = 5\ \angle 90°$

$0 - j\,5 = \sqrt{0+25}\ \underline{/\ \tan^{-1}(-\infty)} = 5\ \angle\text{-}90°$

The polar form is much more convenient for multiplying or dividing complex numbers. The multiplication in polar form is reduced to addition of the angles and subtraction for division. The following rules apply:

MULTIPLICATION OF COMPLEX NUMBER

Multiply the magnitudes but add the angles, algebraically.

24 ∠40° x **2 ∠30° = 48 ∠70°**

24 ∠40° x **- 2 ∠30° = - 48 ∠70°**

12 ∠-20° x **3 ∠-30° = 36 ∠-50°**

12 ∠40° x **4 ∠-30° = 48 ∠10°**

When you multiply by a real number, just multiply the magnitudes:

4 x **2 ∠30° = 8 ∠30°**	**- 4** x **2 ∠30° = - 8 ∠30°**
4 x **2 ∠-30° = 8 ∠-30°**	**- 4** x **- 2 ∠30° = 8 ∠30°**

This rule follows from the fact that a real number has a phase angle of 0° when adding zero degree to any angle, the sum equals to the same angle.

DIVISION FOR COMPLEX NUMBER

Divide the magnitudes but subtract the angles, algebraically:

24 ∠40° ÷ **2 ∠30° = 12 ∠(40° - 30°) = 12 ∠10°**

12 ∠20° ÷ **3 ∠50° = 4 ∠(20° - 50°) = 4 ∠-30°**

24 ∠-20° ÷ **(-6) ∠50° = - 4 ∠(-20° - 50°) = -4 ∠-70°**

To divide by a real number, just divide the magnitudes:

12 ∠30° ÷ **2 = 6 ∠30°**

-18 ∠-30° ÷ **2 = -9 ∠-30°**

This rule is also a special case that follows from the fact that a real number has a phase angle of 0°. When you subtract 0° from any angle, the remainder equals the same angle.

For the opposite case, however, when you divide a real number by a complex number the angle of the denominator changes its sign in the numerator.

As examples:

$$\frac{10}{5\angle 30^{o}} = \frac{10\angle 0^{o}}{5\angle 30^{o}} = 2\ \angle(0° - 30°) = 2\ \angle\text{-}\ 30°$$

$$\frac{10}{5\angle -30^{o}} = \frac{10\angle 0^{o}}{5\angle -30^{o}} = 2\ \angle[0° -(- 30°)] = 2\ \angle{+}\ 30°$$

CONVERTING POLAR TO RECTANGULAR FORM

Complex numbers in polar form are convenient for multiplication and division, but they cannot be added or subtracted. When complex numbers in polar form are to be added or subtracted, they must be converted into rectangular form.

Consider the impedance Z $\angle\theta$ in polar form. Its value is the hypotenuse of a right triangle with sides formed by the real term and **j** term in rectangular coordinates, (Fig. 4.2-6).

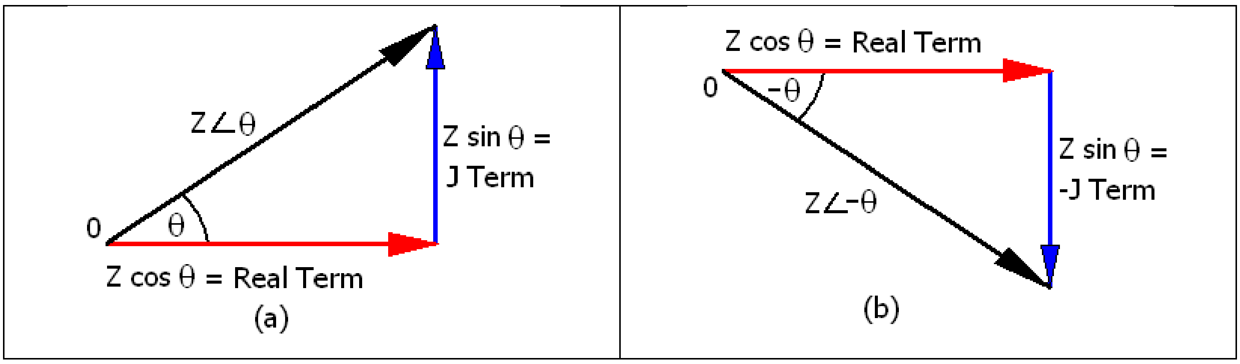


Fig. 4.2-6 Polar to Rectangular Conversion

Therefore, the polar form can be converted to rectangular form by finding the horizontal and vertical sides of the right triangle. Specifically:

Real Term = Z cos θ

j Term = Z sin θ

In Fig. 4.2-6(b), assume that Z ∠θ is **5 ∠37°**. The **sine** of **37°** is **0.6** and its cosine is **0.8**.

To convert to rectangular form:

Real Term = Z cos θ = 5 x **0.8 = 4**

j Term = Z sin θ= 5 x **0.6 = 3**

Therefore: **5 ∠37° = 4 + j 3**

In Fig. 4.2-6(b), the values are the same but the j term is negative when θ is negative. The negative angle has a negative **j** term because the opposite side is in the fourth quadrant, where the sine is negative. However, the real number is still positive because the cosine is positive. These rules apply for angles in the first or fourth quadrant, from 0° to 90° or from 0° to -90°. As examples:

- **14.14 ∠45° = 10 + j10**
- **14.14 ∠-45° = 10 - j10**
- **10 ∠90° = 0 + j10**
- **10 ∠-90° = 0 - j10**
- **100 ∠60° = 50 + j 86.6**
- **100 ∠-60° = 50 - j 86.6**
- **100 ∠30° = 86.6 + j50**
- **100 ∠-30° = 86.6 - j50**

When computing from one form to the other, whether the angle is smaller or greater than 45° the **j** term is smaller or larger than the real term, respectively. For angles between 0 and 45°, the **j** term must be smaller than the real term. For angles between 45° and 90°, the **j** term must be larger than the real term.

EXAMPLE 4.2-1

Calculate the total impedance and the voltage across each element for the circuit shown in Fig. 4.2-7.

$$Z_T = 2 + j\,4 + 4 - j\,12$$

$$= 6 - j\,8 = 10\ \angle{-53°}$$

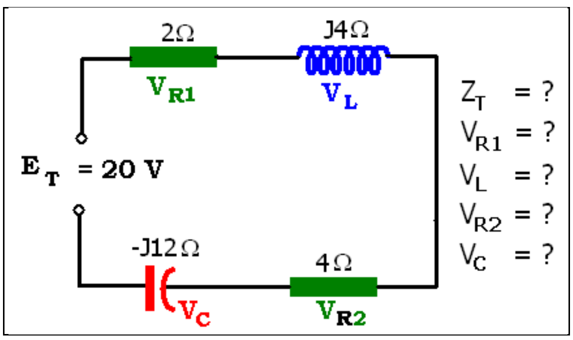


Fig. 4.2-7 Total Impedance

The angle of -53° for $\mathbf{Z_T}$ means that the current are 53° out of phase with voltage.

$\mathbf{I_T = (E_T/Z_T) = (20 \angle 0°) / (10 \angle -53°) = 2 \angle 53° \ A}$

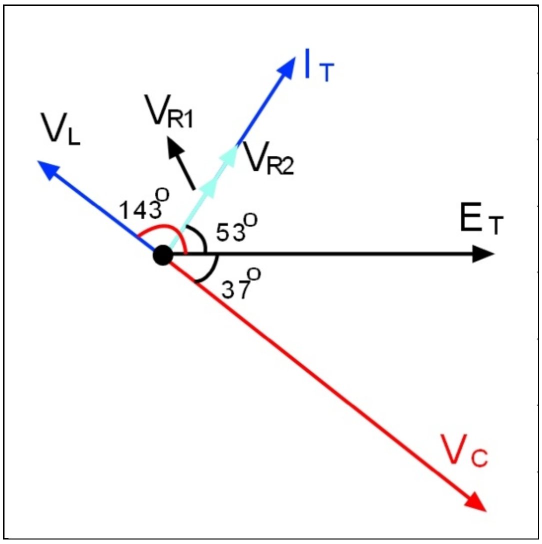


Fig. 4.2-8 Phase Angle

$E_t = 20 \angle 0°$

$V_{R1} = I_T \times R_1 = 2 \angle 53° \times 2 = 4 \angle 53° \ V$

$V_L = I_T \times X_L = 2 \angle 53° \times 4 \angle 90° = 8 \angle 143° \ V$

$V_{R2} = I_T \times R_2 = 2 \angle 53° \times 4 = 8 \angle 53° \ V$

$V_C = I_T \times X_C = 2 \angle 53° \times 12 \angle -90° = 24 \angle -37° \ V$

These voltages are shown in Fig. 4.2-8.

The vector sum for the voltage across each element for the circuit must equal the applied voltage. Using rectangular form:

$V_{R1} = 4 \angle 53° \ V = 2.408 + j\ 3.196$

$V_L = 8 \angle 143° \ V = -6.392 + j\ 4.816$

$V_{R2} = 8 \angle 53° \ V = 4.816 + j\ 6.392$

$V_C = 24 \angle -37° \ V = 19.176 - j\ 14.448$

$V_T = V_{R1} + V_L + V_{R2} + V_C = 20.008 - j\ 0.044$

≈ 20

SUMMARY

- Complex number consists of real part and imaginary part.
- There are two forms to representing complex numbers, polar form and rectangular form.
- The polar form is identified by magnitude and angle.
- The rectangular form is identified by real and imaginary parts.
- The real part is scalar quantity and may be positive or negative.
- The imaginary part is perpendicular to the real part.
- The operator (J) equals ($\sqrt{-1}$).
- The circuit resistance is a real quantity.
- The inductive reactance is a positive imaginary quantity.
- The capacitive reactance is a negative imaginary quantity.
- A combination of R, L & C is represented with complex quantity.
- The complex number can be added, or subtracted in rectangular form.
- The complex number can be multiplied or divided in polar form.

FORMULAE

Rectangular form for Z quantity:

Z = (Real) + J(imaginary)

Polar form for Z quantity:

$Z = Z \angle\theta$

Conversion from rectangular to polar:

$a + J\, b = \sqrt{a^2 + b^2}\ \angle \mathbf{tan^{-1}}\ \boldsymbol{b/a}$

Conversion from polar to rectangular:

$Z \angle\theta = Z \cos\theta + J\, Z \sin\theta$

GLOSSARY

Complex Number:	Two part number consisting of real and imaginary parts
Real part:	Active part
Imaginary part:	Reactive part
Polar coordinate:	A quantity with magnitude and angle
Rectangular coordinate:	Real and Imaginary parts 90º apart from each other
Perpendicular:	A quantity at an angle of 90^o from another quantity

REVIEW EXERCISE

1. Determine the voltage across each element in the Fig. 4.2-9.

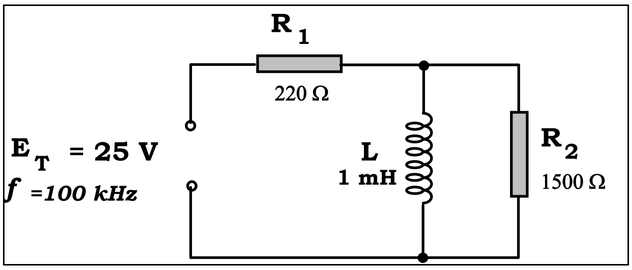


Fig. 4.2-9

2. Determine Z_T, I_T and θ for the circuit in the Fig. 4.2-10.

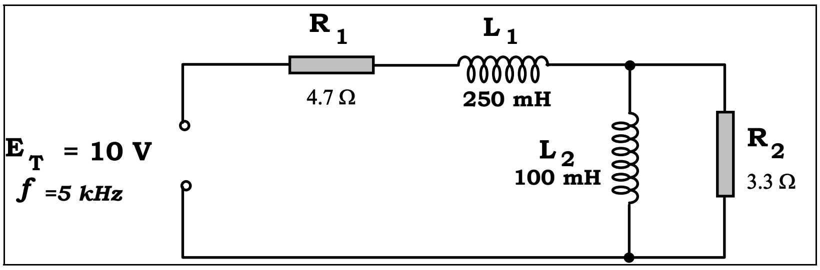


Fig. 4.2-10 RL in Series and Parallel

3. Determine the current passing in the inductors L_1 & L_2 in the Fig. 4.2-11.

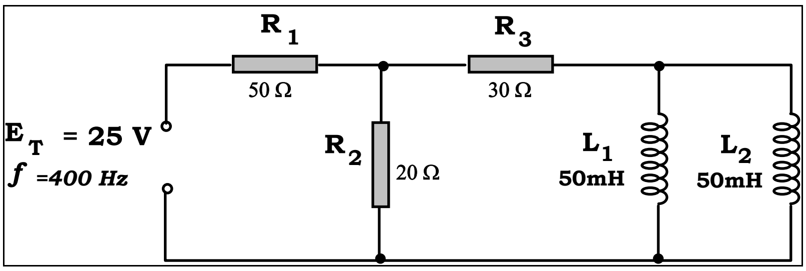
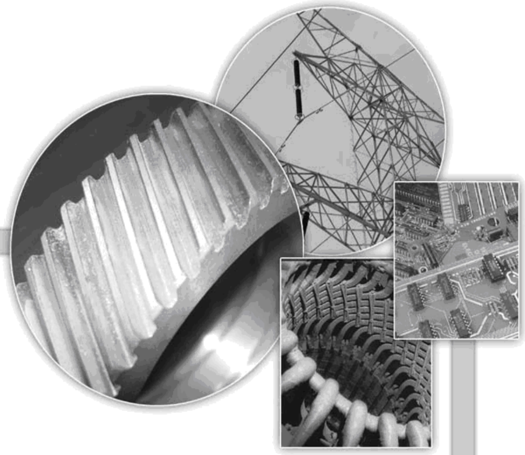


Fig. 4.2-11 RL in Series and Parallel

4. Determine the voltage across the inductors L_1 & L_2 in Q. 3.



LESSON 4.3

PHASOR DIAGRAMS

LESSON 4.3
PHASOR DIAGRAMS

OVERVIEW

This lesson discusses the representation of complex quantities graphically on a vector diagram. The lesson verifies how to add, and subtract vectors using parallelogram method. The purpose of this lesson is to analyze AC circuits to determine currents and voltages as vectorial quantities.

OBJECTIVES

Upon completion of this lesson, the trainees will be able to:

- Represent vectors on the phasor diagram.
- Make phasor additions and subtractions.
- Demonstrate parallelogram method to add or subtract vectors.
- Demonstrate polygon method to add or subtract vectors.
- Apply phasor diagram to analyze AC circuits.

INTRODUCTION

You have learnt from previous lessons that alternating voltages and currents follow a sine wave pattern. If several different voltages or currents of the same frequency are present in a circuit at the same instant of time, these instantaneous voltages and currents can be, more easily, represented by the vector or phasor diagrams. Instantaneous voltages or currents can be completely defined by magnitude and direction in phasors or vectors. Phasors or vectors provide a simple method of representing AC currents and voltages at a given time.

PHASOR ADDITION

Two or more instantaneous values of current (or voltage), of the same frequency and different phase angles, can be added, vectorially. This is done by the "Parallelogram Rule", as shown in Fig. 4.3-1. i_1 and i_2 are original currents, φ phase difference between i_1 and i_2 and i is the resultant current with phase angle θ. It can be seen that the resultant will vary in magnitude and direction depending upon the phase difference of the original phasors. Drawing to scale **(i)** would represent the vectorial sum of $(\mathbf{i_1 + i_2})$:

Resultant = $\sqrt{(i_1^2 + i_2^2 + 2i_1 i_2 \cos \varphi)}$

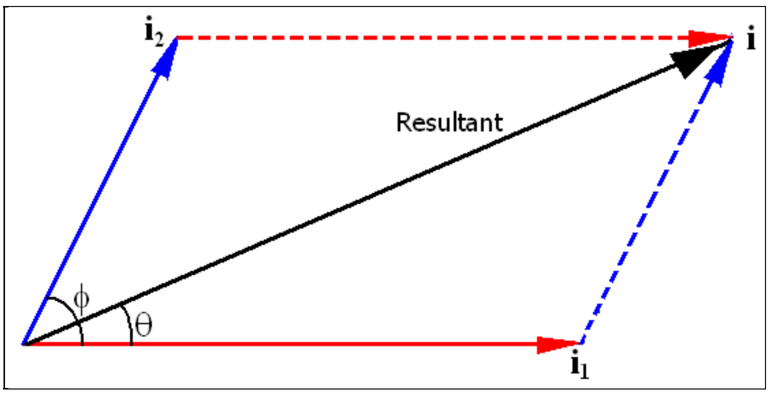


Fig. 4.3-1 Addition of Two Phasor Currents, i_1 and i_2

PHASOR SUBTRACTION

To subtract one phasor quantity **(i_2)** from another **(i_1)**, reverse the direction of the phasor to be subtracted **(i_2)** and add them by parallelogram method, as shown in Fig. 4.3-2. Drawing to scale **(i)** would represent the difference **(i_1 - i_2)** in both direction and magnitude.

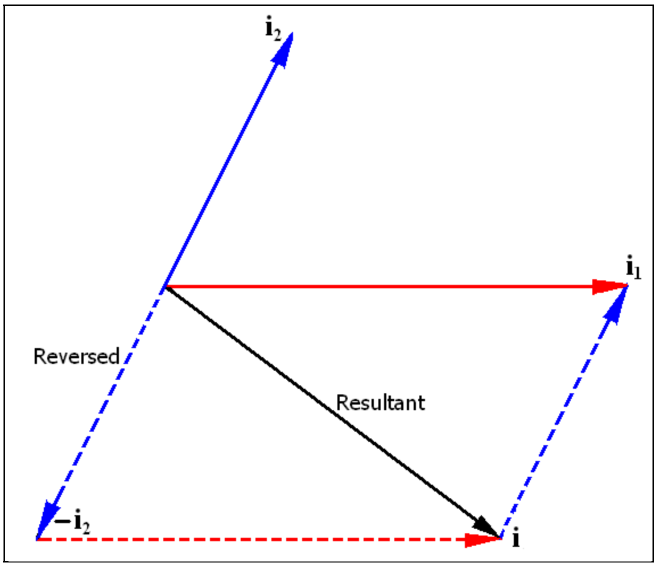


Fig. 4.3-2 Subtracting two Phasor Quantities i_1 and i_2

PRACTICAL CIRCUITS AND PHASOR DIAGRAMS

Resistor and Capacitor in Series

The resultant is the applied voltage **(V)** and is given by the square root of the sum of the squares of the two voltages V_R and V_C, as shown in Fig. 4.3-3 and is given by:

$$\mathbf{V = \sqrt{V_R^2 + V_C^2}}$$

In an RC series circuit, the total current **(I)** is in phase with resistor voltage **(V_R)** but leads the capacitor voltage **(V_C)** by 90°.

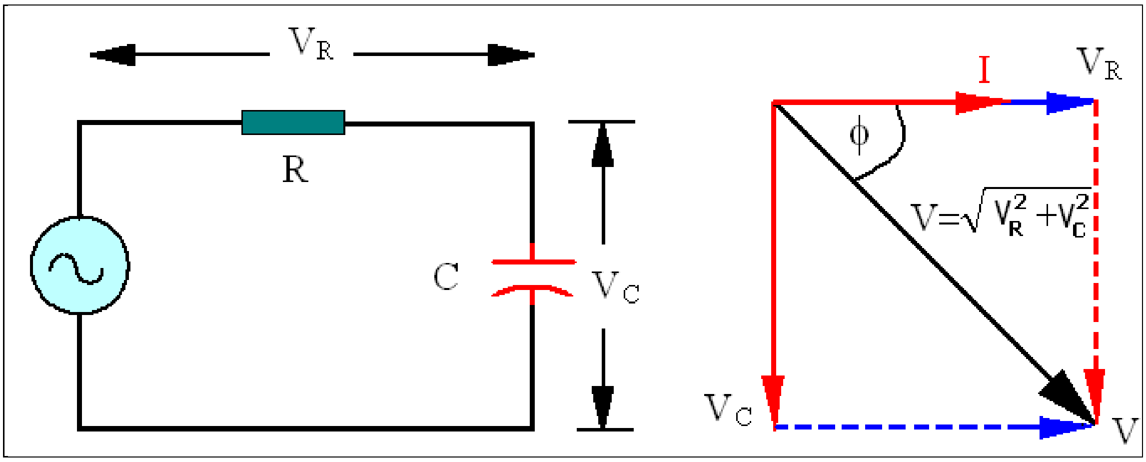


Fig. 4.3-3 Phasor Sum of Two Voltages across Resistor and Capacitor

Resistor and Inductor in Series

The resultant is the applied voltage **(V)** and is given by the square root of the sum of the squares of the two voltages V_R and V_L, as shown in Fig. 4.3-4 and is given by:

$$\mathbf{V=\sqrt{V_R^2+V_L^2}}$$

In an RL series circuit, the total current **(I)** is in phase with resistor voltage **(V_R)** but lags the inductor voltage **(V_L)** by 90°.

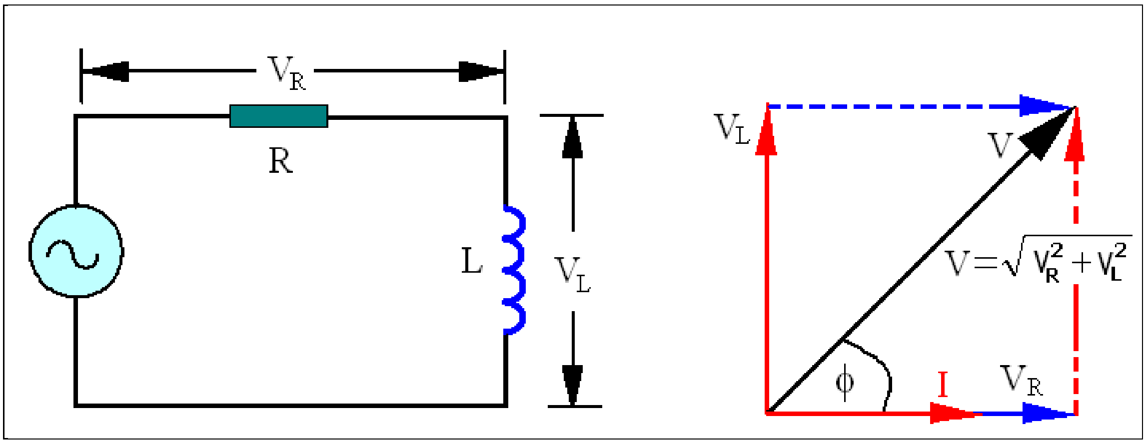


Fig. 4.3-4 Phasor Sum of Two Voltages across Resistor and Inductor

Resistor, Inductor and Capacitor in Series

The resultant is the applied voltage **(V)** and is given by the square root of the sum of the squares of the two voltages V_R and the difference V_L-V_C. The applied voltage will be the phasor sum **(V)** of voltage across the resistor **(V_R)** and the difference between inductor voltage **(V_L)** and the capacitor voltage **(V_C)**, as shown in Fig. 4.3-5 and is given by:

$$\mathbf{V = \sqrt{V_R^2 + (V_L - V_C)^2}}$$

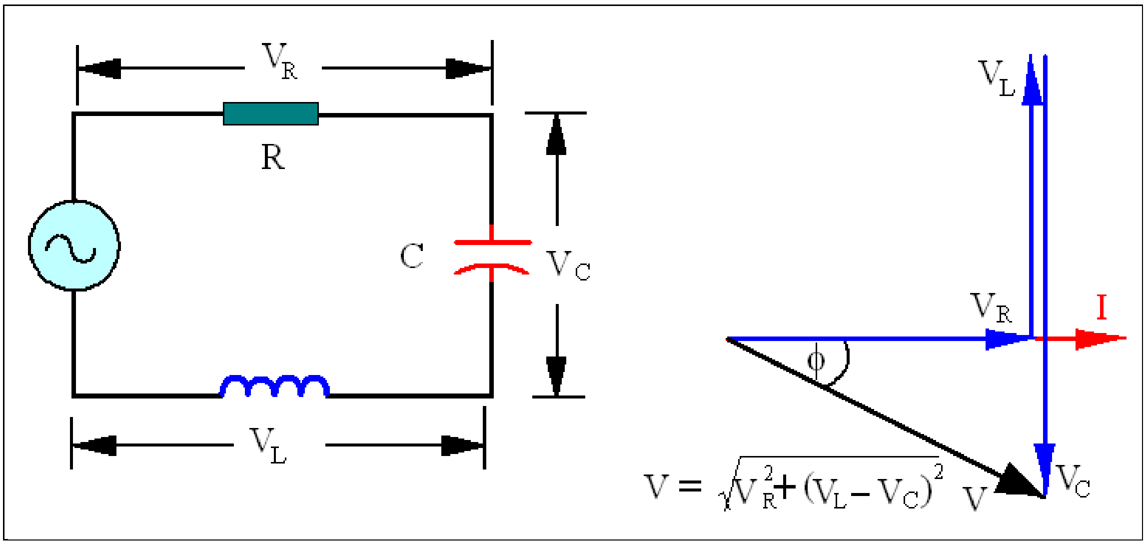


Fig. 4.3-5 Phasor Sum of Three Voltages across Resistor, Inductor and Capacitor

Resistor and Capacitor in Parallel

In this case, we apply the rules as before and once again the common factor is the voltage **(V)** as the reference phasor. The current through resistor in phase with the applied voltage is given by:

$$\mathbf{I_R = V/R}$$

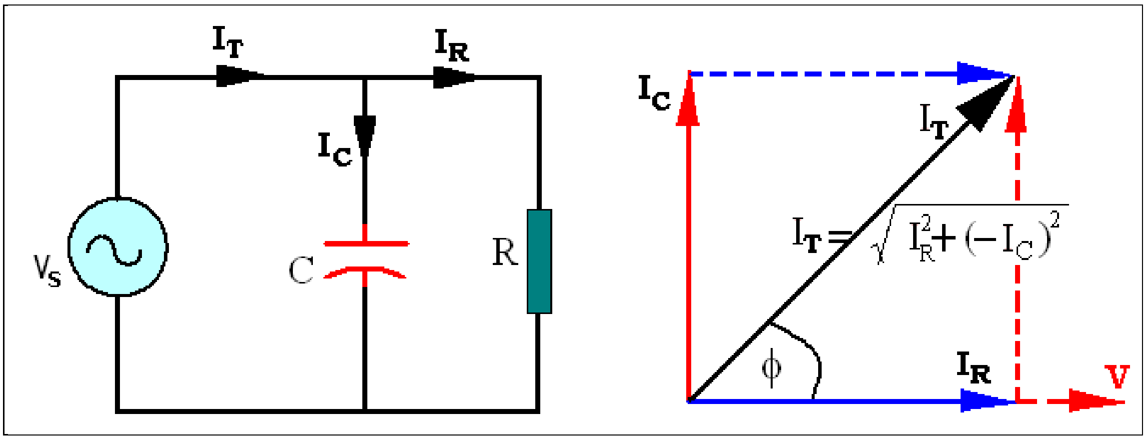


Fig. 4.3-6 Phasor Sum (I_T) of Two Currents through Resistor (I_R) and Capacitor (I_C)

The current through capacitor leading the voltage by 90° is given by:

$I_C = V/X_C$ and $Xc = 1/(2\pi\ f\ C)$

Where:

Xc = Capacitive reactance (Ω)

f = Power line frequency

C = Capacitance (μF)

I_T = resultant current

From the phasor diagram,

$$I_T^2 = I_R^2 + I_C^2$$

$$I_T = \sqrt{I_R^2 + I_C^2}$$

P.F. = Cos ϕ = I_R/I_T, leading

Resistance and Inductance in Parallel

It is not possible to have an inductance without some resistance being present. To simplify our explanation, we shall consider this possibility and show the effect of a 'Pure Inductance' and a 'Pure Resistance in parallel.

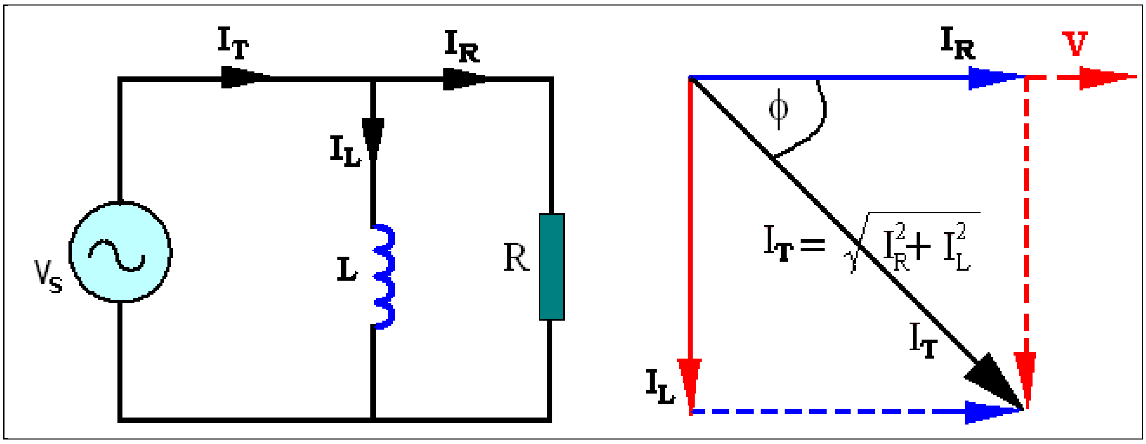


Fig. 4.3-7 Phasor Sum (I_T) of Two Currents through Resistor (I_R) and Inductor (I_L)

In a parallel circuit the common factor is the voltage **(V)** as the reference phasor. The current through resistor in phase with the applied voltage is given by:

$\mathbf{I_R = V/R}$

The current through Inductor lagging the voltage by 90° is given by:

$\mathbf{I_L = V/X_L}$ **and** $\mathbf{X_L = 2\pi f L}$

Where X_L = Inductive reactance (Ω)

f = Power line frequency

L = Inductance (H)

I_T = resultant current

From the phasor diagram,

$$I_T^2 = I_R^2 + I_L^2$$

$$I_T = \sqrt{I_R^2 + I_L^2}$$

P.F. = Cos ϕ = $\mathbf{I_R/I_T}$**,** lagging

Resistance, Capacitor and Inductor in Parallel

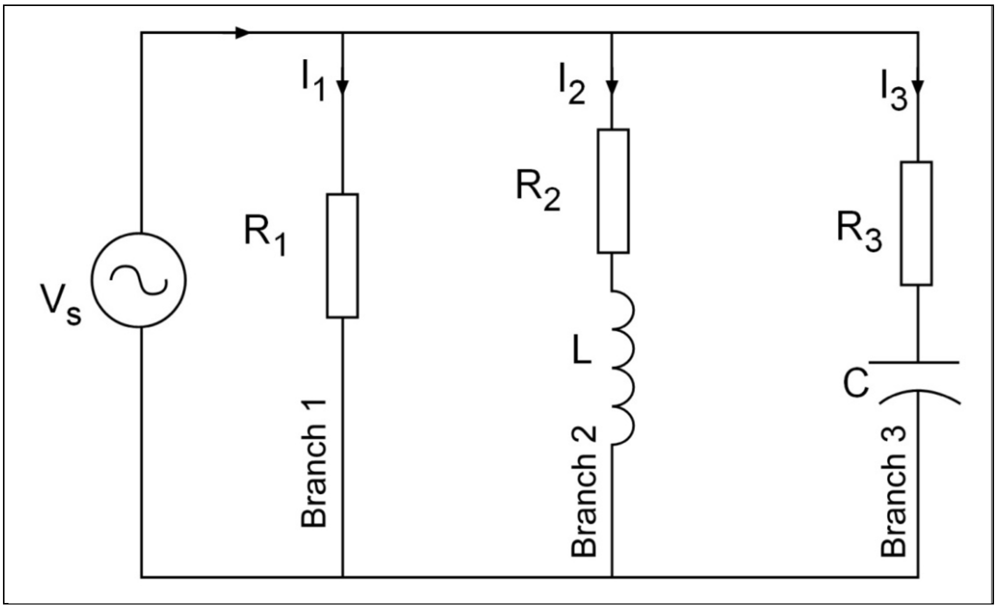


Fig. 4.3-8 Phasor Sum (I_T) of Three Currents I_R, I_C and I_L through Resistor, Capacitor and Inductor

In this case, we treat each branch in turn to find the current angle of lag or lead.

Branch 1: $I_1 = V/R_1, \angle 0°$

Branch 2: $X_L = 2\,\pi\,f\,L,\ Z_2 = (R_2^2 + X_L^2)^{1/2},\quad I_2 = V / Z_2 \quad \mathbf{Cos\ \phi_2 = R_2/Z_2}$

Branch 3: $X_C = 1 / (2\,\pi\,f\,C)\,,\quad Z_3 = (R_3^2 + X_C^2)^{1/2},\quad I_3 = V / Z_3, \quad \mathbf{Cos\ \phi_3 = R_3/Z_3}$

By selecting a suitable scale of 'Amperes per centimeter' and using parallelogram, we can construct a phasor diagram as shown in Fig. 4.3-9 from which, by measurement, the total current, phase angle and the power factor can be obtained.

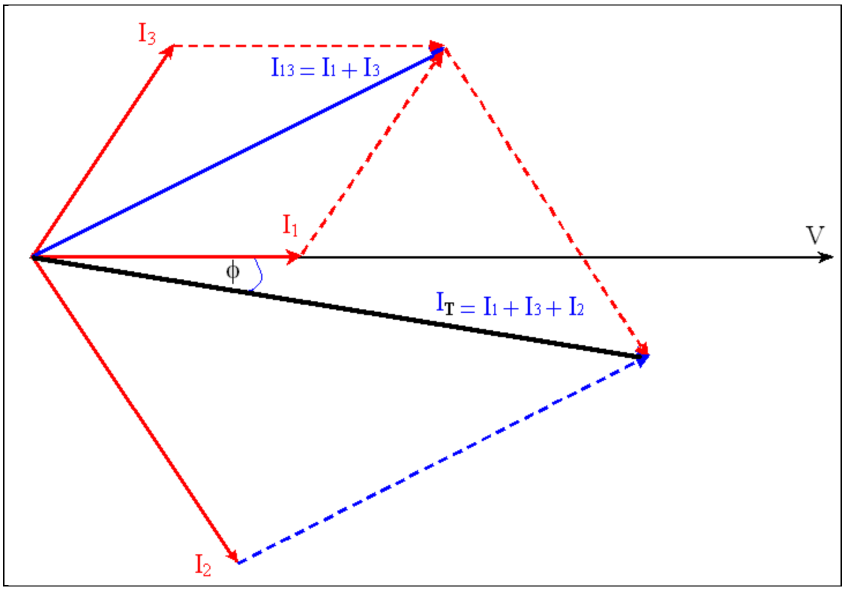


Fig. 4.3-9 Phasor Diagram for Three Currents I_1, I_2 and I_3 in Fig. 4.3-8

Phasor diagram Fig. 4.3-10, using polygon method:

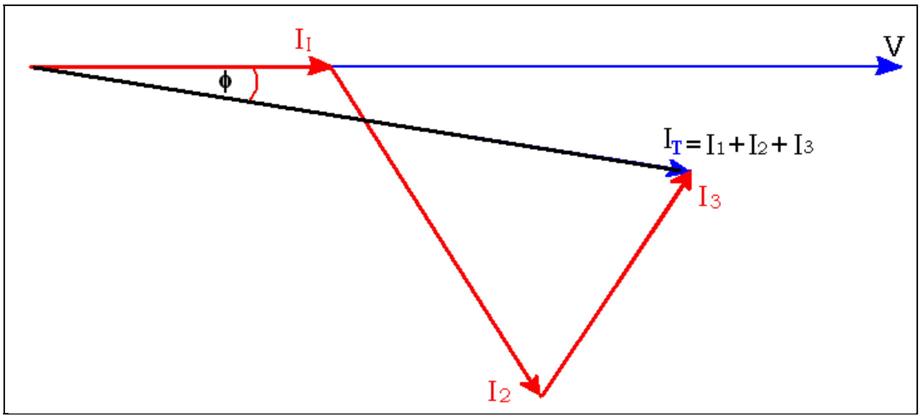


Fig. 4.3-10 Phasor Diagram for Three Currents I_1, I_2 and I_3 in Fig. 4.3-8
(Polygon Method)

By measuring I in each case according to the scale chosen, we can measure the total current. By using a protractor, we can measure the phase-angle between applied voltage and total current lagging, in the example. From "Cosine Table" or calculator, the cosine of the phase angle is determined as the Power Factor (PF).

POWER FACTOR IMPROVEMENT

The method of applying a phasor diagram to Power Factor improvement is shown in Fig. 4.3-11.

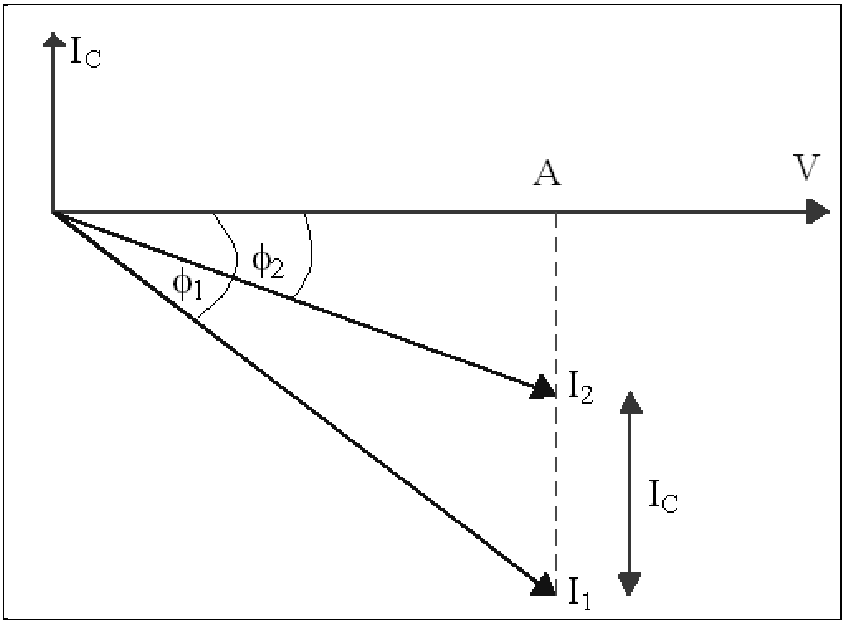


Fig. 4.3-11 Power Factor Improvement

Reference phasor = V

Select suitable scale for current, say (1 cm = 2A)

Before improvement

I_1 = Total current

ϕ_1 = Phase angle

Drop perpendicular from point I_1 to reference phasor. Determine phase angle ϕ_2 from tables for desired improved power factor and draw I_2 to meet perpendicular line (AI_1). Transfer the length I_1 - I_2 = I_C to point of origin. This is the leading reactive component of current required from the capacitor to counteract the amount of lagging reactive component of current, which will give the desired power factor for the circuit. Having obtained length OI_C, we can find the current I_C from the current scale. Knowing applied voltage and current I_C calculate X_C.

$$\mathbf{X_C} = \frac{\mathbf{V}}{\mathbf{I_C}}$$

Also $\mathbf{X_C} = \dfrac{\mathbf{1}}{\mathbf{2\,\pi\,f\,C}}$

From this, we can obtain the value of capacitor required.

THREE VECTORS EQUAL IN MAGNITUDE AND SPACED 120°

The sum of 3 vectors equal in magnitude and spaced 120° is zero is shown in Fig. 4.3-12. The vector ($i_2 + i_3$) is equal and opposite to i_1.

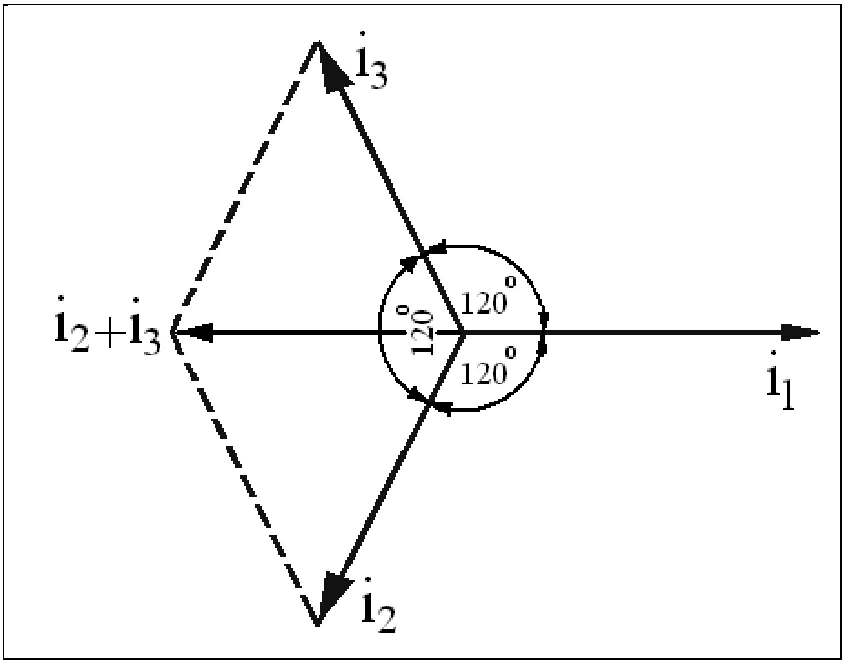


Fig. 4.3-12 Sum of 3 Vectors equal in Magnitude and spaced 120°

PARALLELOGRAM OF VECTORS

If a parallelogram can be drawn to scale to represent two vectors, as shown in the Fig. 4.3-13 below, the resultant is the diagonal of the parallelogram. For example, if the two vectors are A and B. and the angle in between is ϕ, the resultant **(R)** and its phase angle **(θ)** with respect to vector A, can be derived as follows

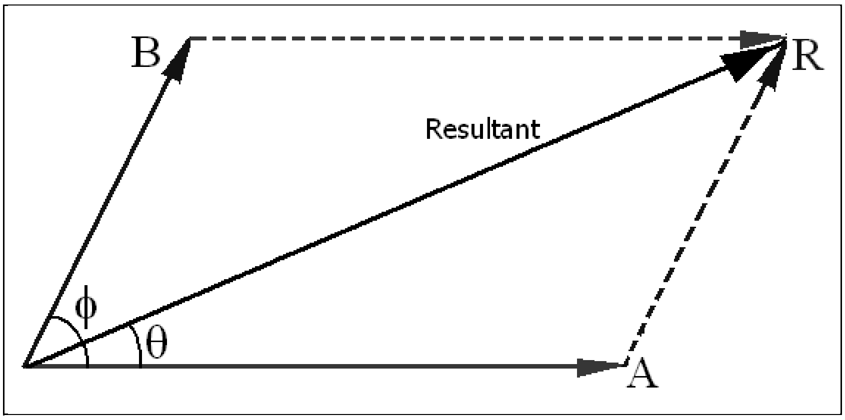


Fig. 4.3-13 Parallelogram of Two Vectors and Resultant

$$\mathbf{R} = \sqrt{\mathbf{A}^2 + \mathbf{B}^2 + 2\mathbf{AB}\mathbf{Cos}\phi}$$

$$\boldsymbol{\theta} = \mathbf{Tan}^{-1} \frac{(\mathbf{B}\,\mathbf{Sin}\phi)}{\mathbf{A} + \mathbf{B}\,\mathbf{Cos}\phi}$$

For example, if A = 1, B = 2, and $\phi = 60°$

$$\mathbf{R} = \sqrt{\mathbf{A}^2 + \mathbf{B}^2 + 2\mathbf{AB}\mathbf{Cos}\phi}$$

$$\mathbf{R} = \sqrt{\mathbf{1}^2 + \mathbf{2}^2 + \mathbf{2} \times \mathbf{1} \times 2\,\mathbf{Cos}\,60°} = \mathbf{2.646}$$

$$\boldsymbol{\theta} = \mathbf{Tan}^{-1} \frac{(\mathbf{B}\,\mathbf{Sin}\phi)}{\mathbf{A} + \mathbf{B}\,\mathbf{Cos}\phi} \qquad \boldsymbol{\theta} = \mathbf{Tan}^{-1} \frac{(\mathbf{2}\,\mathbf{Sin}\,60°)}{\mathbf{1} + \mathbf{2}\,\mathbf{Cos}\,60°} = \tan^{-1} 0.866 \approx \mathbf{41°}$$

The above values can also be found by drawing a phasor diagram to scale and measuring the unknown values.

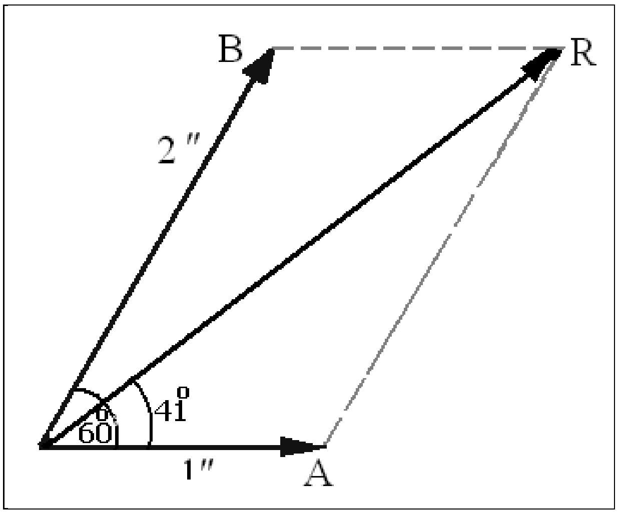


Fig. 4.3-14 Resultant of Two Vectors in Example

SUMMARY

- Instantaneous voltages or currents can be represented by magnitude and direction in algebraic phasors or vector diagram.
- In an RC series circuit, the total current **(I)** is in phase with resistor voltage **(V_R)** but leads the capacitor voltage **(V_C)** by 90°.
- In an RL series circuit, the total current **(I)** is in phase with resistor voltage **(V_R)** but lags the inductor voltage **(V_L)** by 90°.
- The resultant is given by the square root of the sum of the squares of the two voltage or current phasors.
- Parallelogram method is used to add or subtract two vectorial quantities.
- Polygon method is used to add more than two vectorial quantities.
- Vector diagram helps to solve AC series or parallel circuits.

FORMULAE

Resultant = $\sqrt{}$ **($i_1^2 + i_2^2 + 2i_1\, i_2 \cos \varphi$)** Addition of two phasor currents, i_1 and i_2

Series Circuits

$V = \sqrt{V_R^2 + V_C^2}$ Addition of two phasor voltages V_R and V_C

$V = \sqrt{V_R^2 + V_L^2}$ Addition of two phasor voltages V_R and V_L

$V = \sqrt{V_R^2 + (V_L - V_C)^2}$ Addition of three phasor voltages V_R, V_L and V_C

Parallel Circuits

$I_T = \sqrt{I_R^2 + I_C^2}$ Addition of two phasor currents, i_R and i_C

P.F. = Cos ϕ = I_R/I_T, leading

$I_T = \sqrt{I_R^2 + I_L^2}$ Addition of two phasor currents, i_R and i_L

P.F. = Cos ϕ = I_R/I_T, lagging

Parallelogram of Two Vectors and Resultant

$$R = \sqrt{A^2 + B^2 + 2AB\cos\phi}$$

$$\theta = \mathrm{Tan}^{-1} \frac{(B \sin \phi)}{A + B \cos \phi}$$

GLOSSARY

Vector:	Quantity has magnitude and angle.
Parallelogram method:	Way to add two vectors graphically.
Polygon method:	Way to add many vectors graphically.
Resultant vector:	Total summation of added vectors.

REVIEW EXERCISE

1- Convert the following rectangular forms to polar forms and draw its polar phasor diagram:

1- $10 + j10$.

2- $-10 - j10$.

3- $j10$.

4- $-J10$.

2- Convert the following polar forms to rectangular forms and draw its rectangular phasor diagram:

1- $10\angle 240^o =$

2- $15\angle -30^o =$

3- $-12\angle 90^o =$

4- $5\angle 120^o =$

3- For the given RC series circuit shown in Fig. 4.3-15, draw the two phasor voltages V_R = 80V & V_C = 60V and their resultant in the phasor diagram, approximately, to scale.

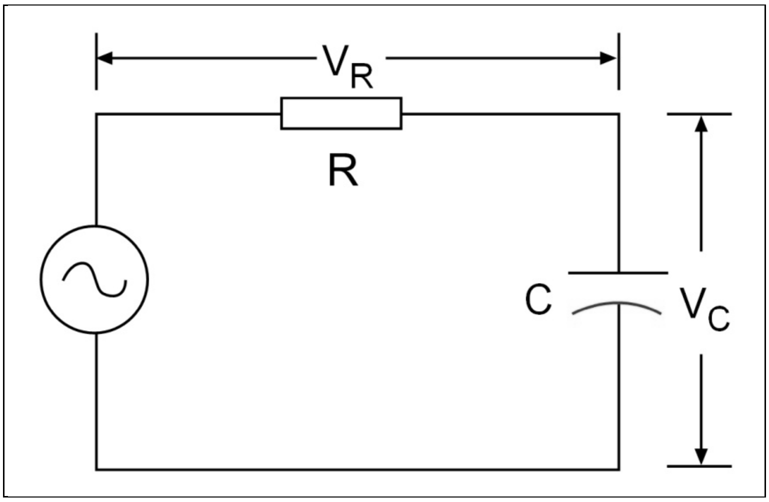


Fig. 4.3-15 Phasor Sum of Two Voltages across Resistor and Capacitor

4- For the given RL series circuit, draw the two phasor voltages V_R = 40V & V_L = 30V and their resultant in the phasor diagram, approximately, to scale.

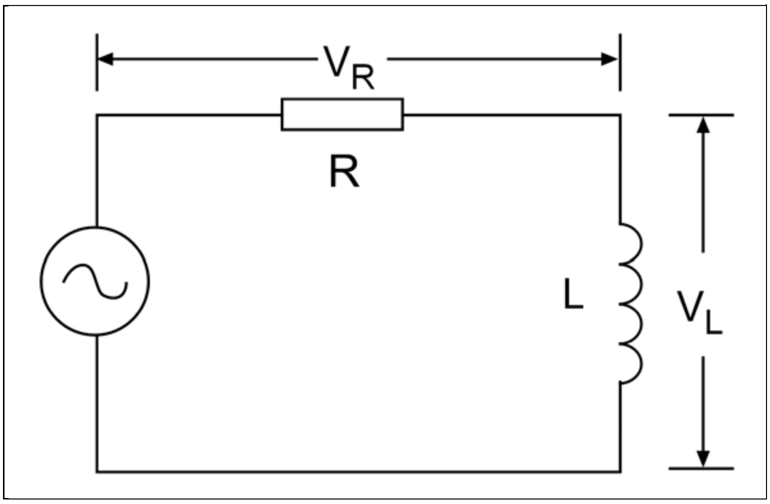


Fig. 4.3-16 Phasor Sum of Two Voltages across Resistor and Inductor

5- Given a series AC circuit with current flow of 2A through a resistor (R = 20 Ω), an inductor (X_L = 40 Ω), and a capacitor (X_C = 60 Ω).

a) Draw a schematic diagram of the series circuit.

b) Calculate the voltage drop across each series component.

c) Determine the applied voltage using phasor diagram.

d) Determine the phase angle of the circuit.

e) Determine the power factor.

6- A parallel circuit has the following five branches:

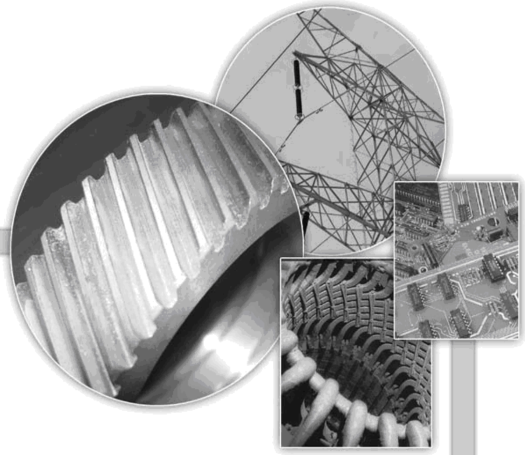
Three resistors of 30 Ω each, an X_L of 600 Ω, an X_C of 400 Ω and applied voltage 100 V. Determine the following using phasor diagram.

a) Draw a schematic diagram.

b) The total impedance of the circuit.

c) The impedance phase angle.

d) The total line current.



LESSON 4.4

SYMMETRICAL COMPONENTS

LESSON 4.4
SYMMETRICAL COMPONENTS

OVERVIEW

In this lesson, trainees learn the concepts of positive, negative and zero sequence components in the power system and solve related system problems. Symmetrical components are a powerful tool for determining currents and voltages in an unbalanced three phase system. The unbalance of currents and voltages in a power system usually occurs because of a fault and could damage the system unless prevented by some protective means. The method of symmetrical components greatly simplifies the process of calculating short circuit currents and voltages.

OBJECTIVES

- Upon completion of this lesson, the trainees will be able to:
- Describe positive, negative and zero sequence components.
- Identify the operator 'a'.
- Solve problems using symmetrical components.

INTRODUCTION

Power systems are large and complex three-phase systems. In the normal operating conditions, these systems are in balanced condition and hence can be represented as an equivalent single phase system. However, a fault can cause the system to become unbalanced. Specifically, the unsymmetrical faults - open circuit, line to ground, line to line, and line to line to ground faults cause the system to become unsymmetrical. The single-phase equivalent system method of analysis cannot be applied to such unsymmetrical systems. Symmetrical components are used to analyze power systems under unsymmetrical conditions.

The symmetrical component method is a modeling technique that permits systematic analysis and design of three-phase systems. Decoupling a complex three-phase network into three simpler networks appears complicated phenomena in more simplistic terms. This transformation represents an unbalanced three-phase system by a set of three balanced three-phase systems.

Consider a set of three-phase unbalanced voltages designated as V_A, V_B, and V_C. These phase voltages can be resolved into the following three sets of components, as shown in Fig. 4.4-1.

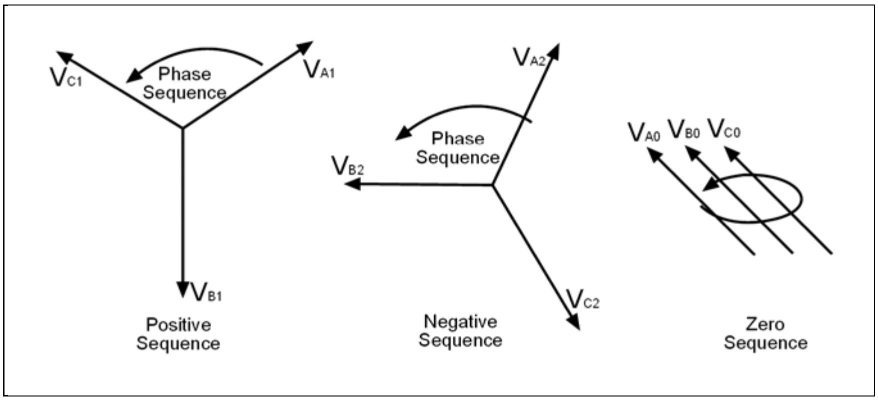


Fig. 4.4-1 Three-phase Voltage represented by Symmetrical Components

1. Positive-sequence components, consisting of three vectors equal in magnitude, displaced from each other by 120^o in phase, and having the same phase sequence as the original vectors, designated as V_{A1}, V_{B1}, and V_{C1}.

2. Negative-sequence components, consisting of three vectors equal in magnitude, displaced from each other by 120^o in phase, and having the phase sequence opposite to that of the original vectors, designated as V_{A2}, V_{B2}, and V_{C2} still rotating CCW.

3. Zero-sequence components, consisting of three vectors equal in magnitude, and with zero phase displacement from each other, designated as V_{A0}, V_{B0}, and V_{C0}.

Since each of the original unbalanced vectors is the sum of its components, the original vectors expressed in terms of their components are

$V_A = V_{A1} + V_{A2} + V_{A0}$

$V_B = V_{B1} + V_{B2} + V_{B0}$

$V_C = V_{C1} + V_{C2} + V_{C0}$

The combination of a set of three unbalanced vectors from the three sets of symmetrical components is shown in Fig. 4.4-2.

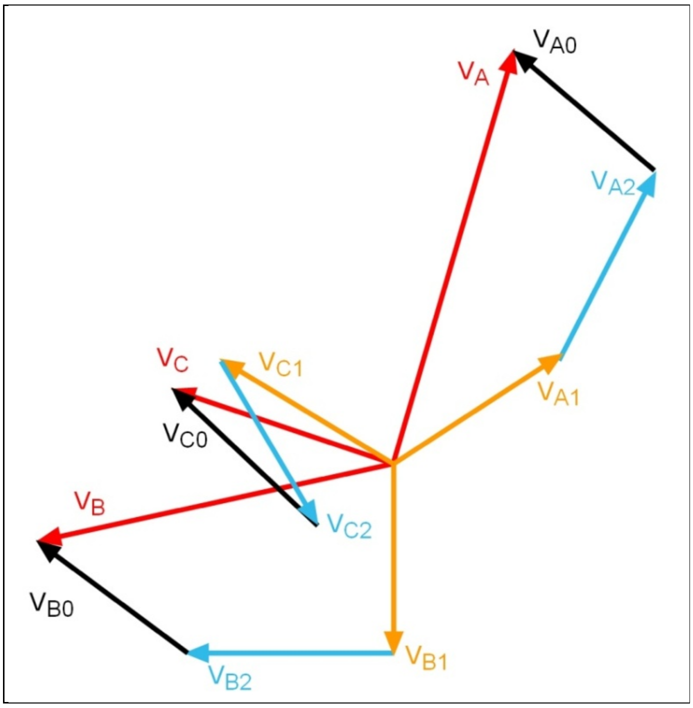


Fig. 4.4-2 Graphical Addition of Symmetrical Components

THE (*a*) OPERATOR

The relation between the symmetrical components reveals that the phase displacement among them is either 120^o or 0^o**.** Using this relationship, only three independent components is sufficient to determine all the nine components. For this purpose an

operator, which rotates a given vector by 120^o in the positive direction (counter clock wise), is very useful. The letter '***a***' is used to designate such a complex operator of unit magnitude with an angle of 120^o as shown in Fig. 4.4-3.

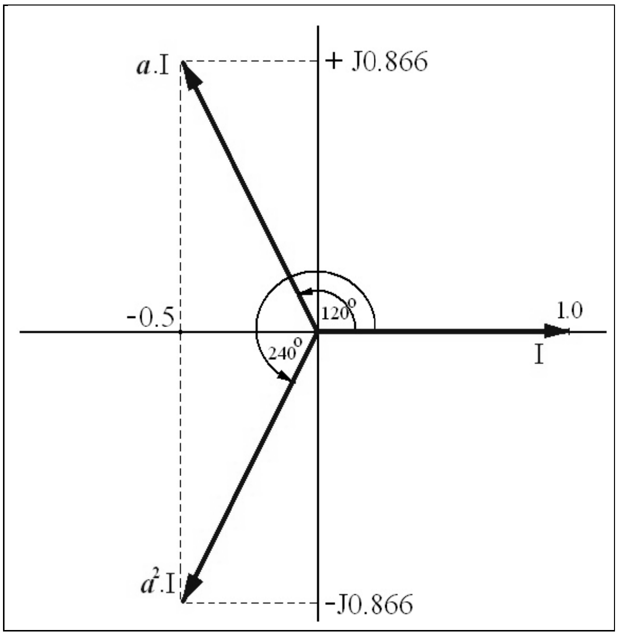


Fig. 4.4-3 Representing of Operator ***a***

The three equations have the typical form of three symmetrical vectors.
The polar and rectangular forms of operators $\boldsymbol{a}$, $\boldsymbol{a}^2$, and $\boldsymbol{a}^3$ are:

$\boldsymbol{a} = 1\angle 120^\circ$ (in polar form)

Or $\boldsymbol{a} = 1\ (\cos 120^o + J \sin 120^o) = -0.5 + j\ 0.866$ (in rectangular form)

$\boldsymbol{a}^2 = 1\ \angle 240^\circ$ (in polar form)

Or $\boldsymbol{a}^2 = 1\ (\cos 240^o + J \sin 240^o) = -0.5 - j\ 0.866$ (in rectangular form)

$\boldsymbol{a}^3 = 1\ \angle 0^\circ$ (in polar form)

Or $\boldsymbol{a}^3 = 1\ (\cos 0^o + J \sin 0^o) = 1 + j\ 0$ (in rectangular form)

If the operator '***a***' is applied to a vector twice in succession, the vector is rotated through 240^o. Similarly, three successive applications of the operator '***a***' rotate the vector through 360^o. To reduce the number of unknown quantities, let the symmetrical

components of V_B and V_C can be expressed as product of some function of the operator '***a***' and the corresponding component of V_A.

Thus,

$V_{B1} = \boldsymbol{a}^2 V_{A1}$ $V_{B2} = \boldsymbol{a} V_{A2}$ $V_{B0} = V_{A0}$

$V_{C1} = \boldsymbol{a} V_{A1}$ $V_{C2} = \boldsymbol{a}^2 V_{A2}$ $V_{C0} = V_{A0}$

Using these relations the unbalanced vectors can be written as

$V_A = V_{A0} + V_{A1} + V_{A2}$

$V_B = V_{A0} + \boldsymbol{a}^2 V_{A1} + \boldsymbol{a} V_{A2}$

$V_C = V_{A0} + \boldsymbol{a} v_{A1} + \boldsymbol{a}^2 V_{A2}$

The same rules apply to current vectors.

To reduce the number of unknown quantities, let the symmetrical components of I_B and I_C expressed as product of some function of the operator '***a***' and the corresponding component of I_A.

Thus,

$I_{B1} = \boldsymbol{a}^2 I_{A1}$ $I_{B2} = \boldsymbol{a} I_{A2}$ $I_{B0} = I_{A0}$

$I_{C1} = \boldsymbol{a} I_{A1}$ $I_{C2} = \boldsymbol{a}^2 I_{A2}$ $I_{C0} = I_{A0}$

Using these relations the unbalanced vectors can be written as

$I_A = I_{A0} + I_{A1} + I_{A2}$

$I_B = I_{A0} + \boldsymbol{a}^2 I_{A1} + \boldsymbol{a} I_{A2}$

$I_C = I_{A0} + \boldsymbol{a} I_{A1} + \boldsymbol{a}^2 I_{A2}$

Another significant property, that is:

$1 + a + a^2 = 0$

Because, $1 + (-0.5 + j0.866) + (-0.5 - j0.866) = 0$

This property is important because it shows that the sum of three balanced vectors is always zero:

$I_A + I_B + I_C = 0$

EXAMPLE 4.4-1

What are the polar and rectangular forms of vectors representing phase currents in a balanced three phase system, if the phase current is $I_A = 50 \angle -30°$.

SOLUTION

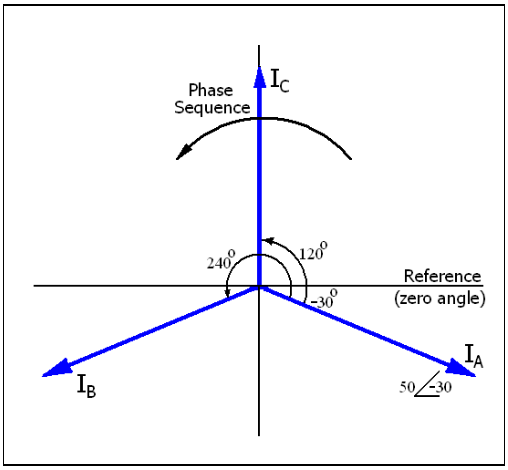


Fig. 4.4-4

$I_A = 50 \angle -30°$

$I_B = \boldsymbol{a}^2 I_A = 1 \angle 240° \times 50 \angle -30° = 50 \angle 210°$

$I_C = \boldsymbol{a}\, I_A = 1 \angle 120° \times 50 \angle -30° = 50 \angle 90°$

The rectangular forms of these vectors are:

$I_A = 50\,[\cos(-30°) + j\sin(-30°)] = (0.866 - j0.5) = \mathbf{43.3 - j25}$

$I_B = \boldsymbol{a}^2 I_A = (-0.5 - j0.866)(43.3 - j25) = \mathbf{-43.3 - j25}$

$I_C = \boldsymbol{a}\, I_A = (-0.5 + j0.866)(43.3 - j25) = \mathbf{j50}$

To check the result, verify the balanced current equation:

$I_A + I_B + I_C = 0$

REPRESENTING UNBALANCED SYSTEM

The assumed unbalanced system of vectors consist of three components, one of positive, one of negative and one of zero phase sequence. The original unbalanced vectors may be represented as:

$V_A = V_{A0} + V_{A1} + V_{A2}$

$V_B = V_{B0} + V_{B1} + V_{B2}$ or $V_B = V_{A0} + \boldsymbol{a}^2 V_{A1} + \boldsymbol{a}\, V_{A2}$

$V_C = V_{C0} + V_{C1} + V_{C2}$ $V_C = V_{A0} + \boldsymbol{a}\, V_{A1} + \boldsymbol{a}^2 V_{A2}$

The sequence components are obtained as follows:

$V_{A0} = 1/3\ [V_A + V_B + V_C]$

$V_{A1} = 1/3\ [V_A + \boldsymbol{a}\ V_B + \boldsymbol{a}^2\ V_C]$

$V_{A2} = 1/3\ [V_A + \boldsymbol{a}^2\ V_B + \boldsymbol{a}\ V_C]$

$V_{B0} = V_{A0}$

$V_{B1} = 1/3\ [V_B + \boldsymbol{a}\ V_C + \boldsymbol{a}^2\ V_A]$

$V_{B2} = 1/3\ [V_B + \boldsymbol{a}^2\ V_C + \boldsymbol{a}\ V_A]$

$V_{C0} = V_{A0}$

$V_{C1} = 1/3\ [V_C + \boldsymbol{a}\ V_A + \boldsymbol{a}^2\ V_B]$

$V_{C2} = 1/3\ [V_C + \boldsymbol{a}^2\ V_A + \boldsymbol{a}\ V_B]$

The same rules apply to currents, as follow:

$I_A = I_{A1} + I_{A2} + I_{A0} \quad = \quad I_{A1} + I_{A2} + I_{A0}$

$I_B = I_{B1} + I_{B2} + I_{B0} \quad = \quad \boldsymbol{a}^2\ I_{A1} + \boldsymbol{a}\ I_{A2} + I_{A0}$

$I_C = I_{C1} + I_{C2} + I_{C0} \quad = \quad \boldsymbol{a}\ I_{A1} + \boldsymbol{a}^2\ I_{A2} + I_{A0}$

The sequence components are obtained as follows

$I_{A0} = 1/3\ [I_A + I_B + I_C]$

$I_{A1} = 1/3\ [I_A + \boldsymbol{a}\ I_B + \boldsymbol{a}^2\ I_C]$

$I_{A2} = 1/3\ [I_A + \boldsymbol{a}^2\ I_B + \boldsymbol{a}\ I_C]$

It can be seen that it is only necessary to determine sequence. Currents I_{A1}, I_{A2}, I_{A0} in phase A, then, with the aid of the operators "$\boldsymbol{a}^2$" and "$\boldsymbol{a}$", the current in the other phases can be easily found.

EXAMPLE 4.4-2

Given unbalanced three-phase currents, $I_A = 4 + j3$, $I_B = j8$, $I_C = -2 - j5$. Determine the symmetrical components for each phase current using rectangular form, and polar form.

SOLUTION

(a) Using Rectangular Form

I_{A1} $=1/3\ (I_A + \boldsymbol{a}\, I_B + \boldsymbol{a}^2\, I_C)$

$= 1/3\ [(4 + j3) + (-0.5 + j0.866) \times j8 + (-0.5 - j0.866) \times (-2 - j5)]$

$= 1/3\ [(4 + j3 - j4 - 6.93 + 1 + j1.732 + j2.5 - 4.33]$

$= 1/3\ (-6.26 + j3.23) = -2.09 + j1.077 = \mathbf{2.35\ \angle 153°}$

I_{A2} $= 1/3\ (I_A + \boldsymbol{a}^2\, I_B + a\, I_C)$

$= 1/3\ [(4 + j3) + (-0.5 + j0.866) \times j8 + (-0.5 + j0.866) \times (-2 - j5)]$

$= 1/3\ [(4 + j3 - j4 + 6.93 + 1 - j1.732 + j2.5 + 4.33]$

$= 1/3\ (16.26 - j0.232) = 5.42 - 0.773 = \mathbf{5.42\ \angle 359°}$

I_{A0} $= 1/3\ (I_A + I_B + I_C)$

$= 1/3\ (2 + j6) = 0.33 + J2 = \mathbf{2.11\ \angle 72°}$

I_{B1} $= 1/3\ (I_B + \boldsymbol{a}\, I_C + \boldsymbol{a}^2\, I_A)$

$= 1/3\ (j8 + 1 - j1.73 + j2.5 + 4.33 - 2 - j3.46 - j1.5 + 2.6)$

$= 1.977 + jl.27 = \mathbf{2.35\ \angle 33°}$

I_{B2} $= 1/3\ (I_B + \boldsymbol{a}^2\, I_C + \boldsymbol{a}\, I_A)$

$= 1/3\ (7.93 + j14.19)$

$= 2.64 + j4.73 = \mathbf{5.42\ \angle 119°}$

$I_{B0} \quad = \quad I_{A0} = \mathbf{2.11 \angle 72°}$

$I_{C1} = 1/3\ (I_C + \boldsymbol{a}\, I_A + \boldsymbol{a}^2\, I_B)$

$= 1/3\ (0.33 - j7.04) = \mathbf{2.35 \angle 273°}$

$I_{C2} = 1/3\ (I_C + \boldsymbol{a}^2\, I_A + \boldsymbol{a}\, I_B)$

$= 1/3\ (-\ 8.33 - j13.96) = -\ 2.78 - j4.65 = \mathbf{5.42 \angle 239°}$

$I_{C0} = I_{A0} = 0.667 + J2 = \mathbf{2.11 \angle 72°}$

To prove correct computations, the sum of the three component vectors of each phase should be equal to the given phase vector, thus:

$I_{A1} + I_{A2} + I_{A0} = 4 + j3 \quad = I_A$

$I_{B1} + I_{B2} + I_{B0} = 0 + j8 \quad = I_B$

$I_{C1} + I_{C2} + I_{C0} = -\ 2 - j5 = I_C$

Another proof for correct computation is that the sum of three positive or three negative sequence components should equal zero, thus:

$I_{A1} + I_{B1} + I_{C1} = \quad 0$

$I_{A2} + I_{B2} + I_{C2} = \quad 0$

(b) Using Polar Form

The components I_{A1}, I_{A2} and I_{A0} of vector I_A are first found in the same manner as before:

$I_{A1} = 2.35 \angle 153°$

$I_{B1} = \boldsymbol{a}^2\, I_{A1} = 1\angle 240° \times 2.35 \angle 153° = 2.35 \angle 33°$

$I_{C1} = \boldsymbol{a}\, I_{A1} = 1\angle 120° \times 2.35 \angle 153° = 2.35 \angle 273°$

$I_{A2} = 5.42 \angle 359°$

$I_{B2} = \boldsymbol{a}\, I_{A2} = 1\angle 120° \times 5.42 \angle 359° = 5.42 \angle 119°$

$I_{C2} = \boldsymbol{a}^2\, I_{A2} = 1\angle 120° \times 5.42 \angle 359° = 5.42 \angle 239°$

$I_{A0} = I_{B0} = I_{C0} = 1_0 = 2.11 \angle 72°$

ANALYSIS OF UNBALANCED FAULTS

PHASE-TO-GROUND FAULTS

Assume three-phase system with phase C to ground fault as shown in Fig. 4.4-5.

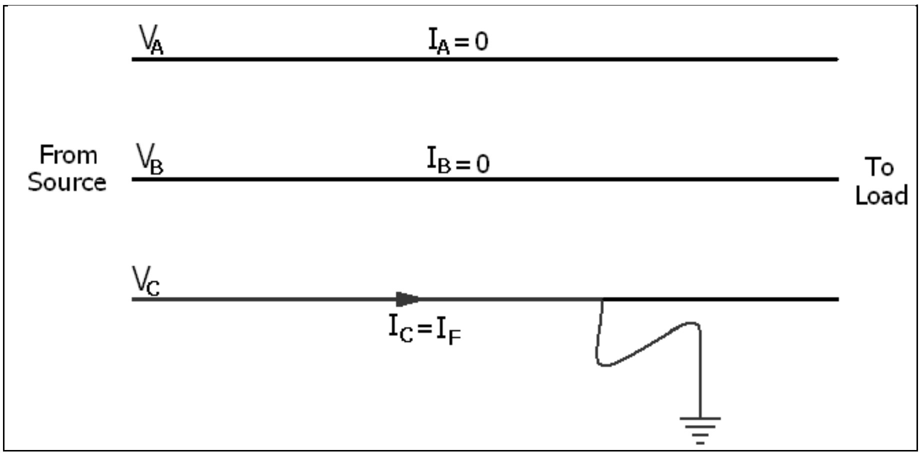


Fig. 4.4-5 Single Line to Ground Fault

$I_A = I_B = 0, \; \& \; I_C = I_F$

$I_{C1} \quad = 1/3\,(I_C + a\, I_A + a^2\, I_B) = I_C\,/3$

$I_{C2} \quad = 1/3\,(I_C + a^2\, I_A + a\, I_B) = I_C\,/3$

$I_{C0} \quad = 1/3\,(I_A + I_B + I_C) = I_C\,/3$

$I_{F1} = I_{F2} = I_{F0} = 1/3\; I_C$

In the phase to ground fault, all symmetrical components of the fault exist.

PHASE-TO-PHASE FAULT

Assume three-phase system with short circuit occurs between phase A & B as shown in Fig. 4.4-6.

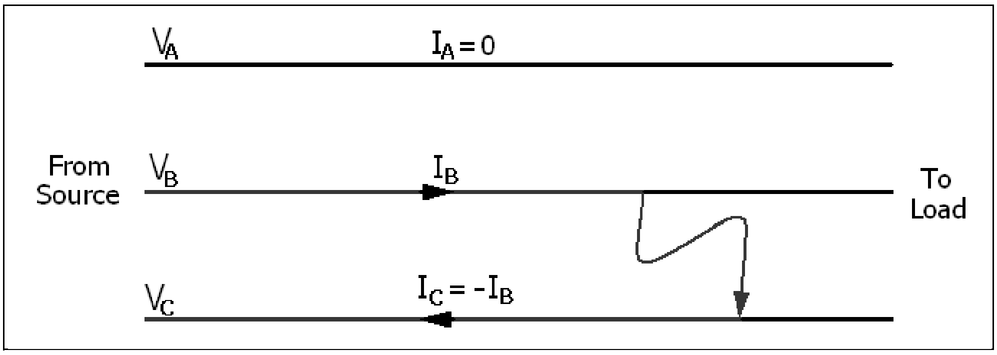


Fig. 4.4-6 Line to Line Fault

$I_A = 0$, $I_B = -I_C = I_F$

$$I_{B1} = 1/3\ (I_B + \boldsymbol{a}\ I_C + \boldsymbol{a}^2\ I_A)$$
$$= 1/3\ (I_B + \boldsymbol{a}\ (-I_B))$$
$$= 1/3\ I_B\ (1 - \boldsymbol{a})$$

$$I_{B2} = 1/3\ (I_B + \boldsymbol{a}^2\ I_C + \boldsymbol{a}\ I_A)$$
$$= 1/3\ (I_B + \boldsymbol{a}^2\ (-I_B))$$
$$= 1/3\ I_B\ (1 - \boldsymbol{a}^2)$$

$$I_{B0} = 1/3\ (I_A + I_B + I_C)$$
$$= 1/3\ (I_B - I_B) = 0$$

Therefore, there is no zero sequence current in the phase-to-phase fault

DOUBLE PHASE TO GROUND FAULT

Assume three-phase system with short circuit between phase B & C to ground as shown in Fig. 4.4-7.

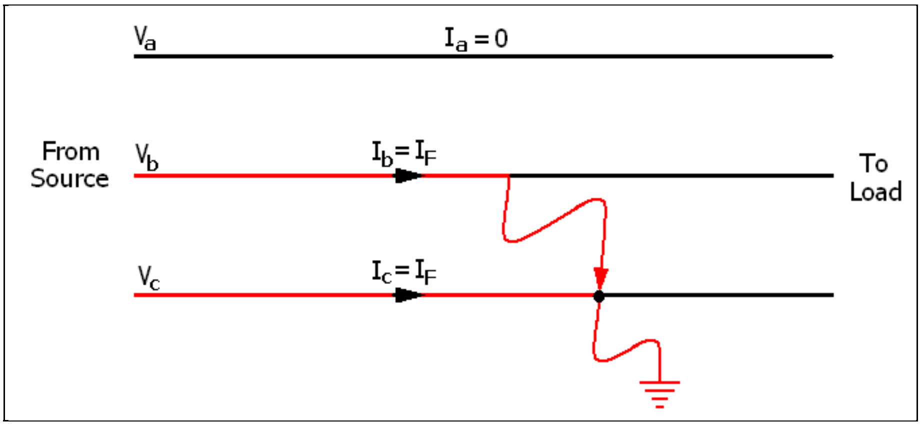


Fig. 4.4-7 Double Line to Ground Fault

In this case, $I_A = 0$, & $I_B = I_C = I_F$

$$
\begin{aligned}
I_{B1} &= 1/3\ (I_B + \boldsymbol{a}\, I_C + \boldsymbol{a}^2 I_A) \\
&= 1/3\ (I_B + \boldsymbol{a}\, I_B) \\
&= 1/3\ I_F\ (1 + \boldsymbol{a})
\end{aligned}
$$

$$
\begin{aligned}
I_{B2} &= 1/3\ (I_B + \boldsymbol{a}^2 I_C + \boldsymbol{a}\, I_A) \\
&= 1/3\ (I_B + \boldsymbol{a}^2 I_B) \\
&= 1/3\ I_F\ (1 + \boldsymbol{a}^2)
\end{aligned}
$$

$$
\begin{aligned}
I_{B0} &= 1/3\ (I_A + I_B + I_C) \\
&= 1/3\ (I_F + I_F) = 2\ I_F\ /3
\end{aligned}
$$

$$
\begin{aligned}
I_{C1} &= 1/3\ (I_C + \boldsymbol{a}\, I_A + \boldsymbol{a}^2 I_B) \\
&= 1/3\ (I_C + \boldsymbol{a}^2 I_C) \\
&= 1/3\ I_F\ (1 + \boldsymbol{a}^2) \\
I_{C2} &= 1/3\ (I_C + \boldsymbol{a}^2 I_A + \boldsymbol{a}\, I_B) \\
&= 1/3\ (I_C + \boldsymbol{a}^2 I_C) \\
&= 1/3\ I_F\ (1 + \boldsymbol{a}^2)
\end{aligned}
$$

$$
\begin{aligned}
I_{C0} &= 1/3\ (I_A + I_B + I_C) \\
&= 1/3\ (I_C + I_C) = 2\ I_F\ /3
\end{aligned}
$$

THREE PHASE FAULTS

Assume three-phase system where short circuit between all the three-phases A, B, & C, as shown in Fig. 4.4-8.

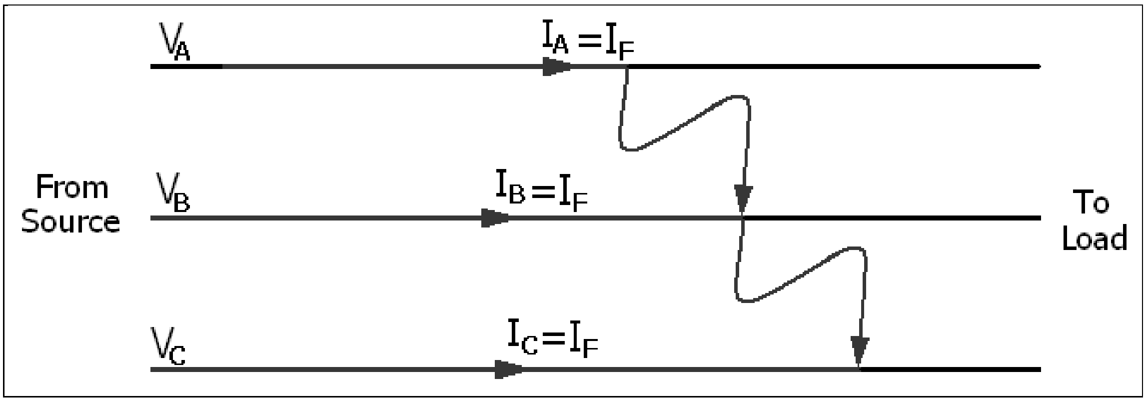


Fig. 4.4-8 Three-phase Short Circuit

$E_A = E_B = E_C = 0$

$E_{F1} = E_{F2} = E_{F0} = 0$

The fault currents in all phases are balanced. The system voltages are reduced, but also balanced in all phases. There is, however, the voltage at the fault point in any phase is zero. Symmetrical components are not effective method to analyze that type of faults.

Example 4.4-3

The circuit in Fig. 4.4-9 shows a phase-to-ground fault with fault current passing through the faulty line only, and return through the main ground of the circuit at the Wye connection.

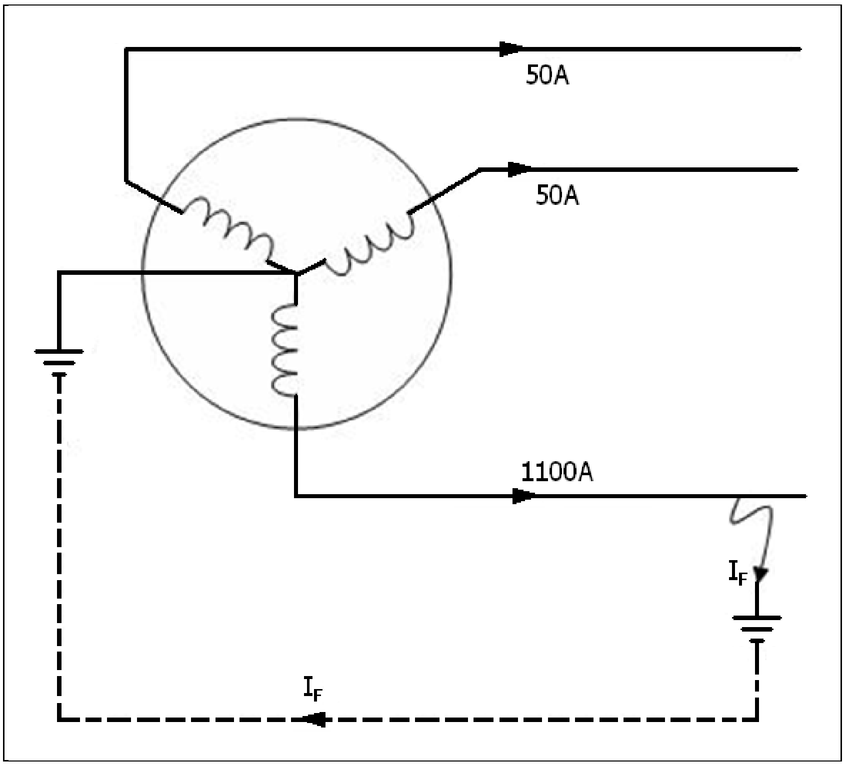


Fig. 4.1-9 Phase to Ground Fault

SOLUTION

$I_A = 50\angle 0°$, $I_B = 50\angle 240°$, & $I_C = 1100\angle -60°$

$I_{A1} = 1/3\ (I_A + \boldsymbol{a}\, I_B + \boldsymbol{a}^2\, I_C)$

$= 1/3\ [(50\angle 0) + (1\angle 120^o)\ (50\angle 240°) + (1\angle 240^o)\ (1100\angle -60^o)]$

$I_{A2} = 1/3\ (I_A + \boldsymbol{a}^2\, I_B + a\, I_C)$

$= 1/3\ [(50\angle 0) + (1\angle 240^o)\ (50\angle 240°) + (1\angle 120^o)\ (1100\angle -60^o)]$

$I_{A0} = I_{B0} = I_{C0} = 1/3\ [(50\angle 0) + (50\angle 240°) + (1100\angle -60^o)]$

$I_{B1} = 1/3\ (I_B + \boldsymbol{a}\, I_C + \boldsymbol{a}^2\, I_A)$

$= 1/3\ [(50\angle 240^o) + (1\angle 120^o)\ (1100\angle -60°) + (1\angle 240^o)\ (50\angle 0^o)]$

$I_{B2} = 1/3\ (I_B + \boldsymbol{a}^2\, I_C + \boldsymbol{a}\, I_A)$

$= 1/3\ [(50\angle 240^o) + (1\angle 240^o)\ (1100\angle -60°) + (1\angle 120^o)\ (50\angle 0^o)]$

$I_{C1} = 1/3\ (I_C + \boldsymbol{a}\ I_A + \boldsymbol{a}^2\ I_B)$

$= 1/3\ [(1100\angle\text{-}60^o) + (1\angle 120^o)\ (50\angle 0°) + (1\angle 240^o)\ (50\angle 240^o)]$

$I_{C2} = 1/3\ (I_C + \boldsymbol{a}^2\ I_A + \boldsymbol{a}\ I_B)$

$= 1/3\ [(1100\angle\text{-}60^o) + (1\angle 240^o)\ (50\angle 0°) + (1\angle 120^o)\ (50\angle 240^o)]$

SUMMARY

- A set of three unbalanced vectors, such as three phase current vectors in a faulty system, can be broken into three sets of balanced vectors.
- In a faulty system, three sets of balanced vectors are known as the 'positive sequence components', 'negative sequence components' and 'zero sequence components'.
- The 'positive sequence components' consist of three vectors equal in magnitude, 120° out of phase and rotating in a direction so that they reach their positive maximum values in a sequence ABC.
- The 'negative sequence components' consist of three vectors equal in magnitude and 120° out of phase and rotating in a direction so that they reach their positive maximum values in a sequence BAC.
- The rotation of all vectors is assumed counterclockwise.
- There is no zero sequence current in the phase-to-phase fault.
- Zero and negative sequence appear in any unbalanced fault to ground.
- At balanced load (normal operation), only positive sequence exists where:
  $V_A = V_{A1}$, $I_A = I_{A1}$, & $I_{A2} = I_{A0} = 0$
- The sum of three balanced vectors is always zero: $I_A + I_B + I_C = 0$
- Using symmetrical components is not a practical method to analyze balanced faults.

FORMULAE

$\boldsymbol{a = 1 \angle 120°}$

$\boldsymbol{a^2 = 1 \angle 240°}$

$\boldsymbol{a^3 = 1}$

The rectangular forms of operators "a" and "a^2":

$a = 1\ (\cos 120° + j \sin 120°) = -0.5 + j\ 0.866$

$a^2 = 1\ (\cos 240° + j \sin 240°) = -0.5 - j0.866$

For three phase balanced system

$V_A = V_A \angle 0°$, $V_B = V_A \angle 240°$, $V_C = V_A \angle 120°$

For Unbalanced three Phase Voltage system:

$E_A = E_{A1} + E_{A2} + E_{A0}$

$E_B = E_{B1} + E_{B2} + E_{B0} \qquad = a^2E_{A1} + aE_{A2} + E_{A0}$

$E_C = E_{C1} + E_{C2} + E_{C0} \qquad = aE_{A1} + a^2E_{A2} + E_{A0}$

Unbalanced three Phase Current system:

$I_A = I_{A1} + I_{A2} + I_{A0}$

$I_B = I_{B1} + I_{B2} + I_{B0} \quad = a^2I_{A1} + aI_{A2} + I_{A0}$

$I_C = I_{C1} + I_{C2} + I_{C0} \quad = aI_{A1} + a^2I_{A2} + I_{A0}$

GLOSSARY

Operator ***a***:	Unit vector makes 120^o in space
Unbalanced fault:	The fault where the three currents or voltages are unequal
Balanced fault:	The fault where the three currents or voltages are equal
Symmetrical:	Balanced
Positive sequence:	The system vectors have the same phase sequence of the original system
Negative sequence:	The system vectors have a phase sequence opposite to that of the original system
Counterclockwise:	Rotate from right to left
Zero sequence:	No vector rotation

REVIEW EXERCISES

1- If $I_{A2} = 5.3 \angle 48°$ find the polar forms of negative sequence currents in the other two phases

2- The following three phase currents are given:

$I_A = 10 \angle -30^o$

$I_B = 10 \angle 90^o$

$I_C = 10 \angle 210^o$

Show if this system is balanced or not?

3- Determine the polar forms of the positive sequence components for vectors I_A = 5, I_B = – 1 + j2 and I_C = – j4.

4- If $I_{A2} = 10 \angle 45°$determine the polar forms of negative sequence components for the other two phases.

5- For unbalanced three phase current system, given:

$I_A = 4 + J3$

$I_B = -3 + J2$

$I_C = -5 – J2$

Find the zero sequence currents of the system.

6- The voltage components for phase A are:

$E_{A1} = 0.5+J0.5$, $E_{A2} = -0.2+J0.4$, and $E_{A0} = -0.6+J0.3$.

Find the phase to ground voltages of the three phases E_A, E_B and E_C.

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Textbook/Workbook

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